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Real electronic
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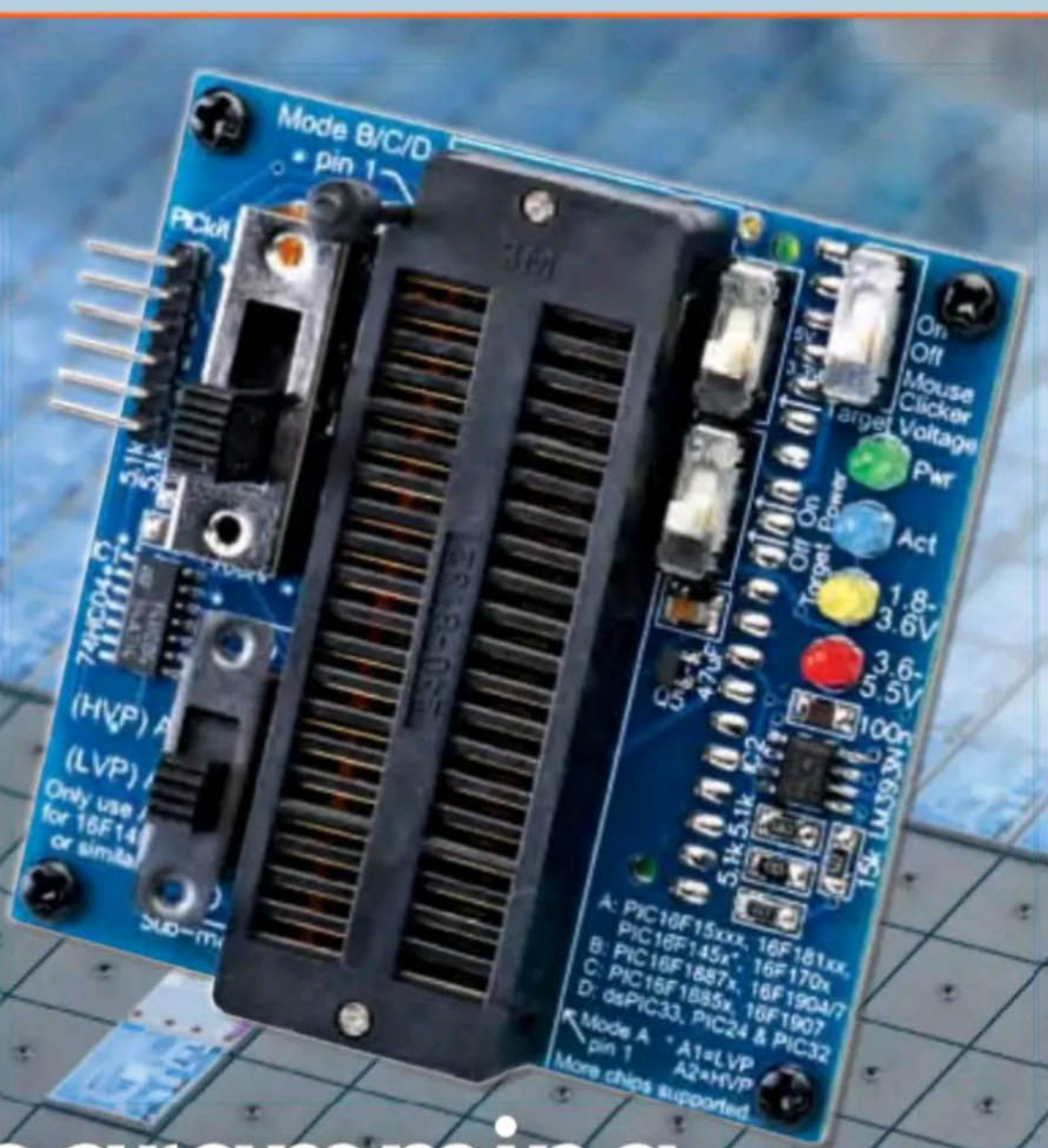

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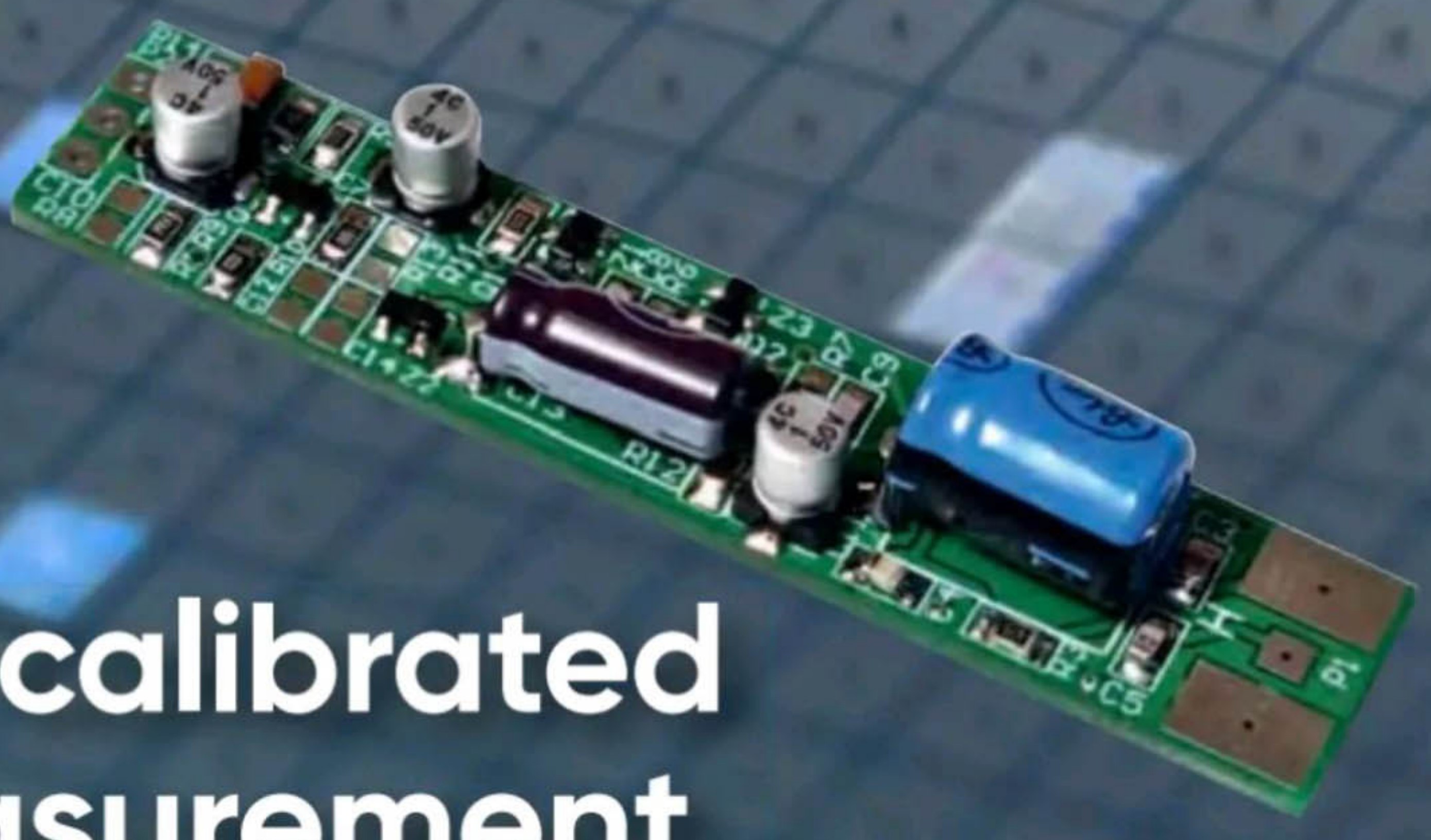

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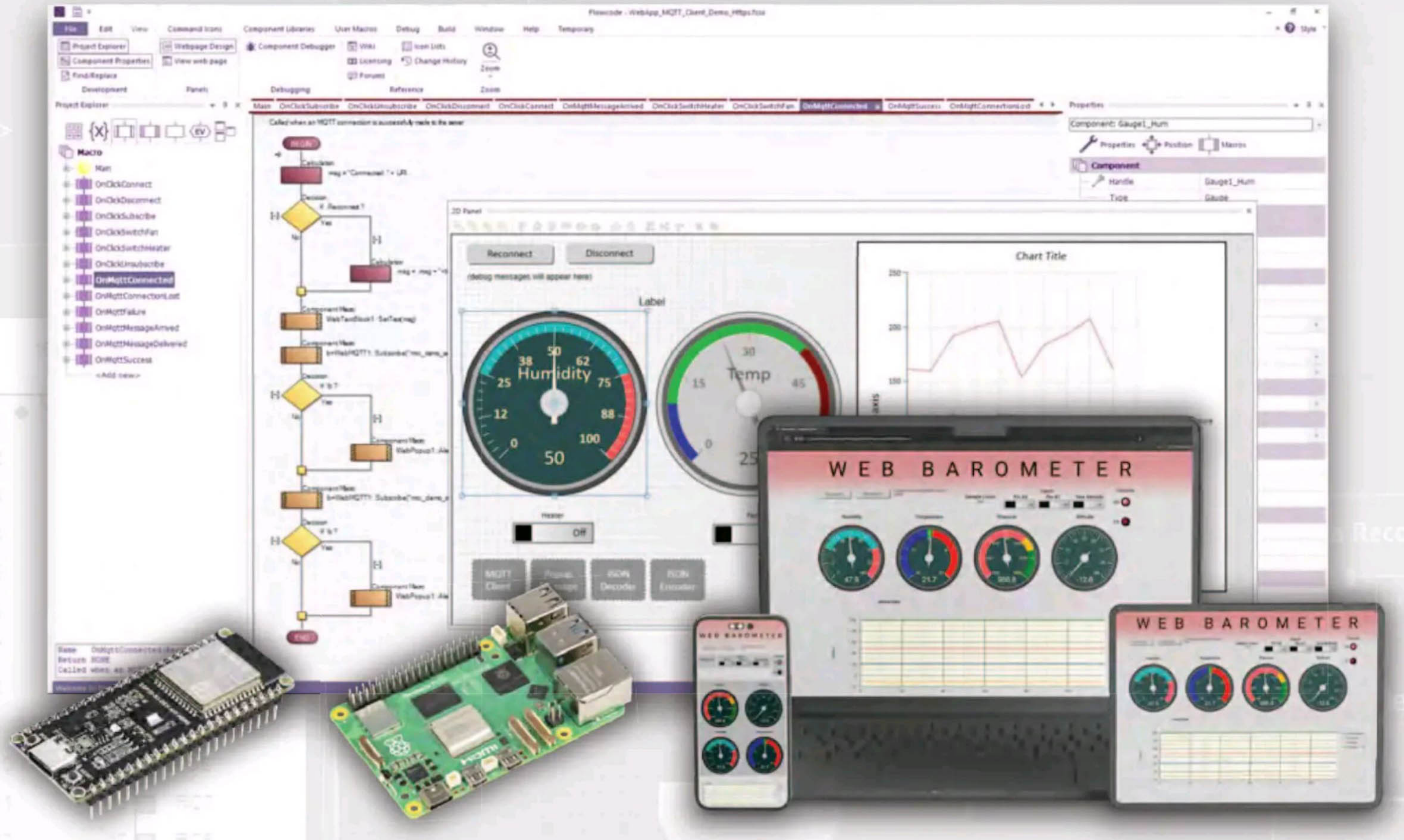
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Practical
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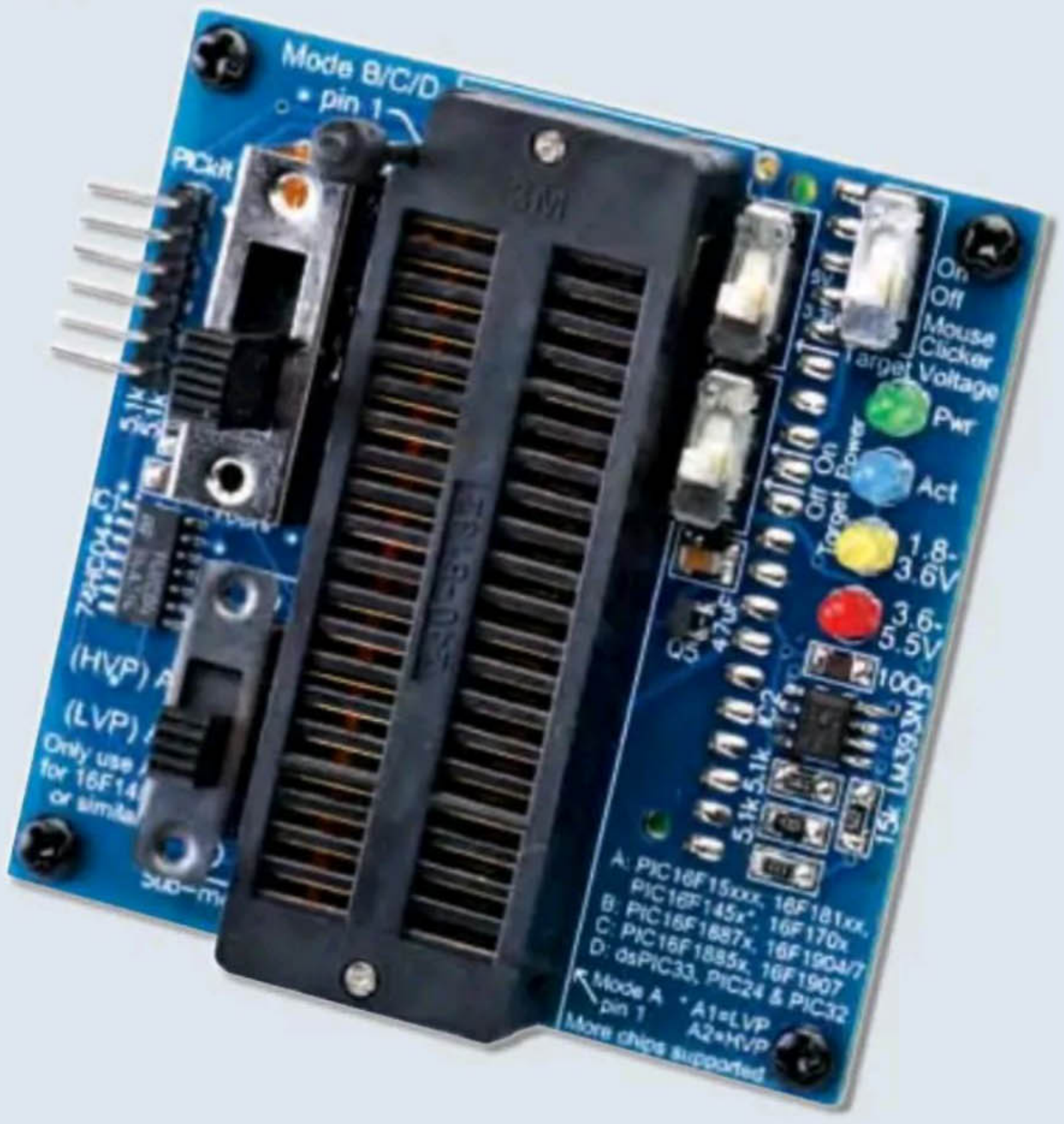

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Questions about articles or projects should be sent to the editor by email: pe@pemag.au

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Some projects and circuits published in *Practical Electronics* employ voltages that can be lethal. Do not build, test, modify or fix any mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

Component supplies
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Editorial

Hello from the other side of the planet

If you read last month's editorial, you will know that Matt Pulzer has retired as Editor and Publisher of Practical Electronics magazine. He asked us to take over due to the close relationship and many similarities between Silicon Chip magazine and *PE*. You will no doubt be aware that *PE* has been republishing our projects and some other articles for well over a decade now.

You will have to judge for yourself how well we have done on our first issue. It has been over six years since I took over Silicon Chip and the feedback since then has generally been positive, so this is not my first rodeo.

As Matt stated last month, we will not be changing any of *PE's* regular content; the articles will remain much the same. I do intend to run an extra article or two each month, as we have a lot of great content that I think readers in the UK, Europe and USA will enjoy.

With a new Editor, you will have to expect some differences. While Australian English is very close to British English, there are a few slight variations in spelling and grammar. You will probably notice that (somewhat unusually), we don't add "ue" to the end of words like analog, dialog and catalog. Yes, those are the American spellings, but the ue-suffix does nothing but make those words needlessly longer.

You may also notice a few slight changes in the magazine's style over time, most of which will (I hope) be beneficial.

Changes to subscription renewals

I had hoped we could keep the subscription system unchanged when we took over the magazine. Unfortunately, it turns out that is not possible as we are not based in the UK. That means we have had to make some adjustments to how subscriptions are paid.

Most subscribers pay via the web. If that describes you, we will be directing you to the Electron Publishing shop from now on (as it was a couple of years ago). You can pay us directly that way, and we will handle the subscription renewal. If you can't pay via the web or don't want to, you will still be dealing with Select Publishing Services.

I don't expect this to cause anyone problems, but please bear with us during the transition. Don't be surprised if your next renewal is a little bit different than the last one. I'm sure we'll have everything running smoothly soon.

Nicholas Vinen, Electron Publishing (Australia)*
Publisher & Editor,
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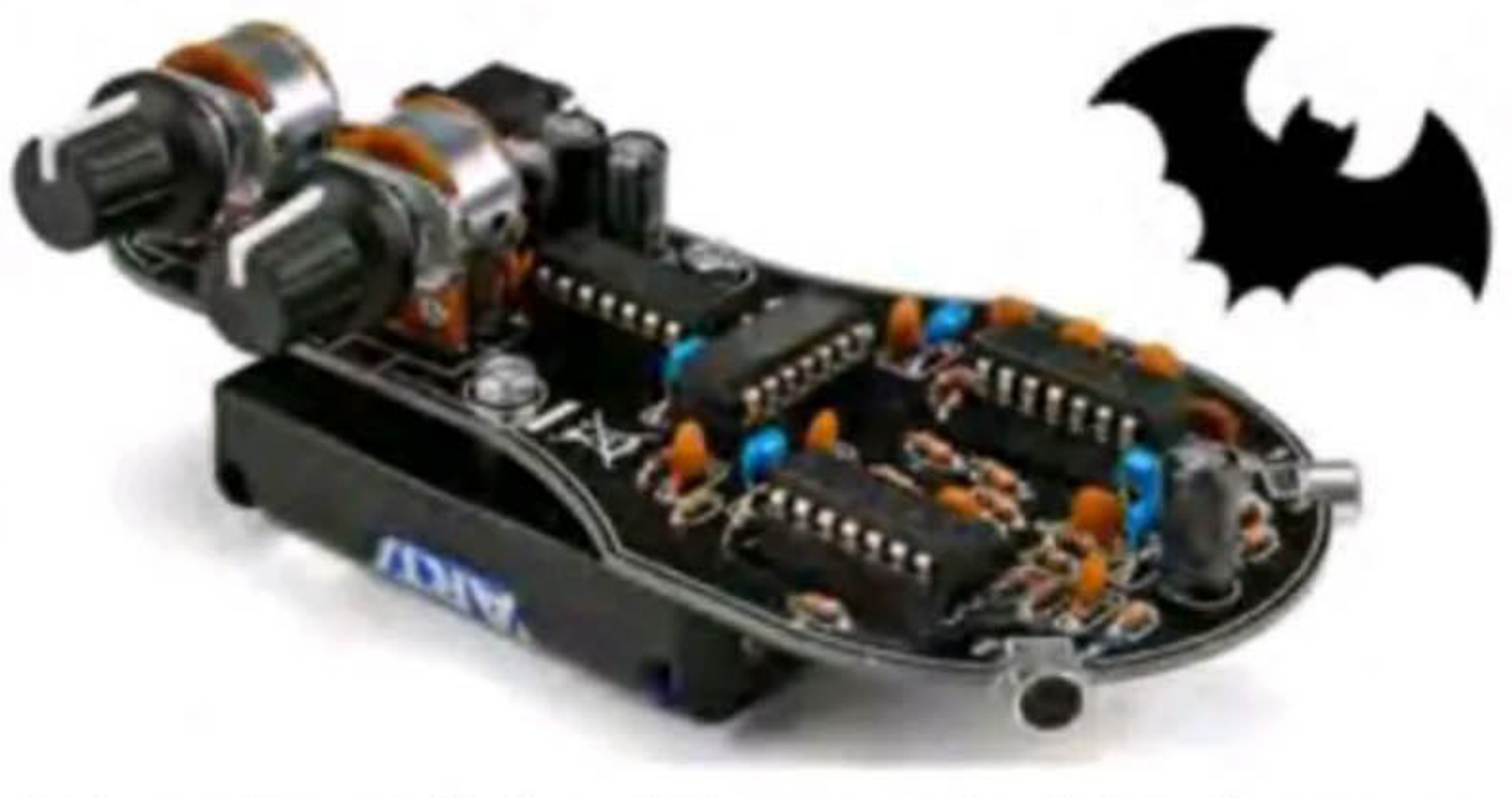

Educational & fun kit converts high frequency sounds (20 - 90kHz) normally imperceptible to humans like bat signals into audible noise. Can also help detect failures in machines, engines, etc. Stereo feature adds the possibility to pinpoint the source. Frequency range 20-90kHz. 3.5mm jack output. 129x60x40mm. Requires 3x AA batteries and stereo headphones (not included).
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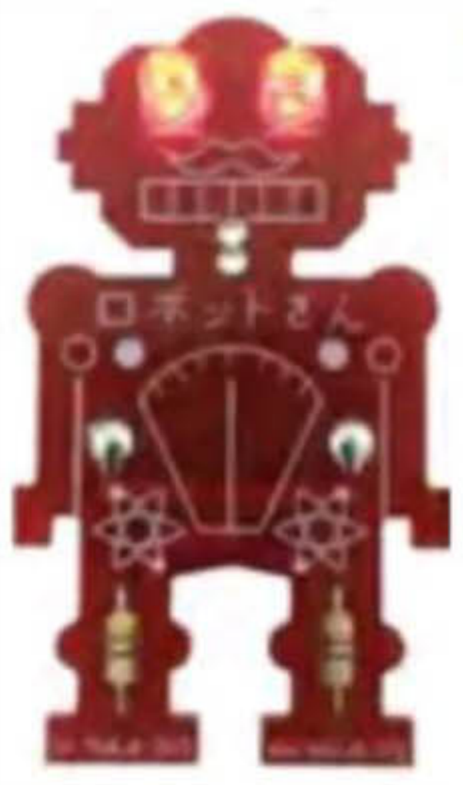

A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
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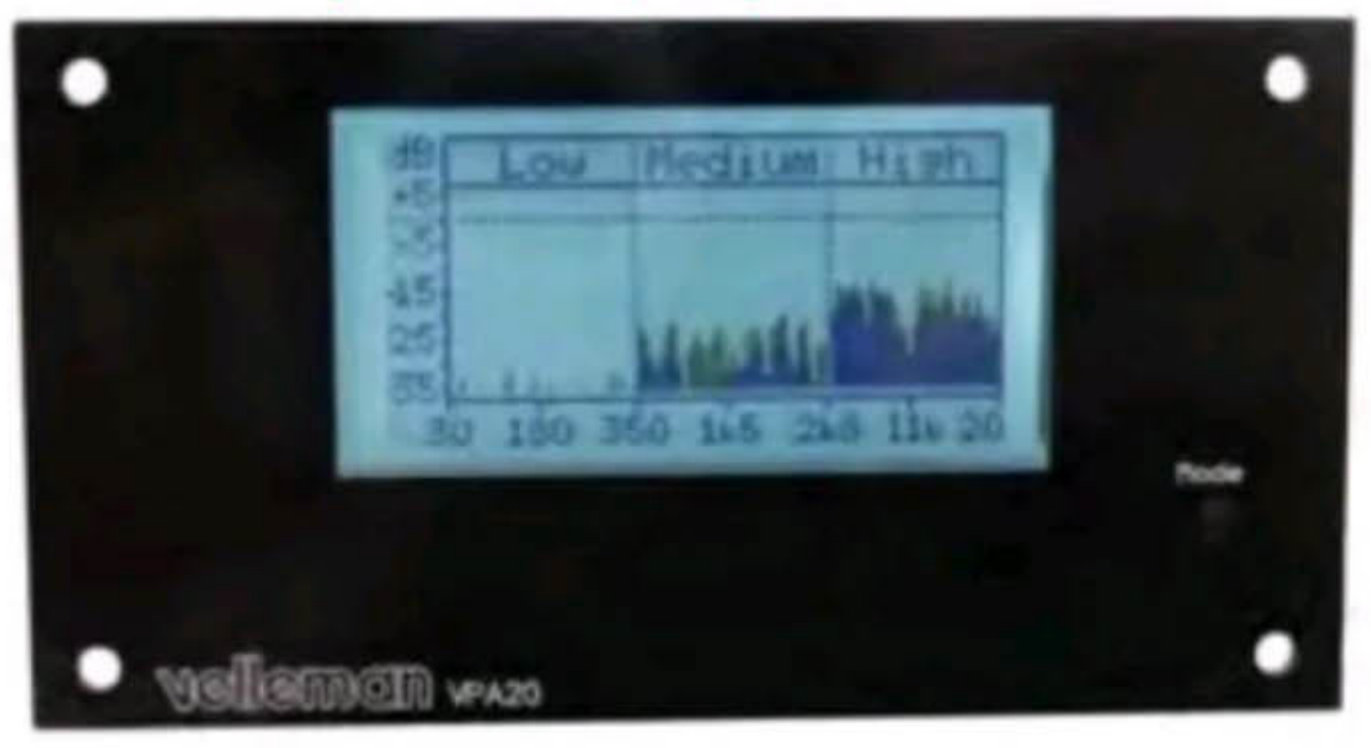

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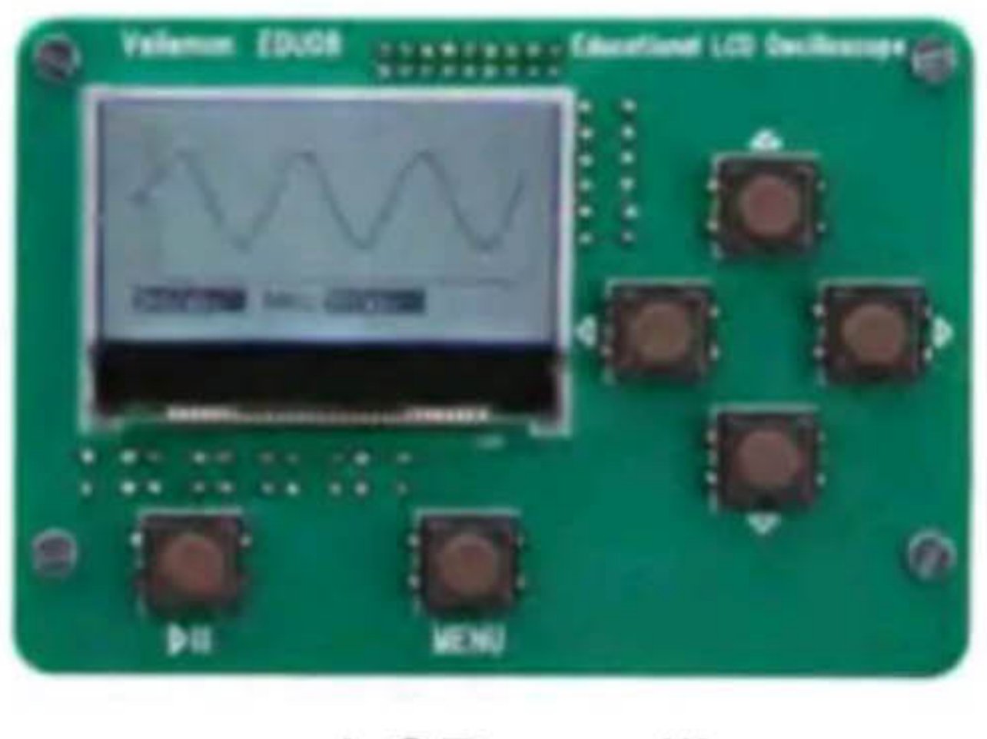

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
*Order Code: WSEDU08 - **£48.54***

I don't want to be a Norbert...

Techno Talk

Max the Magnificent

Things are getting complicated and my head is starting to hurt. Artificial intelligences (AIs) are appearing everywhere. Sometimes they lie to us; now they can detect if we are lying to them! And I just heard about something called "prompt engineering".

Way back in the mists of time (July 2024), I mentioned the 1899 publication of "A Story of the Days to Come" by H. G. Wells.

Set in a dystopian future London of the 22nd century, it's amazing how many of the technology-related concepts described in that book have already come into being. For example, its 'intelligent loudspeakers' are strangely reminiscent (or should we say prescient?) of the Amazon Echo, Google Next or Apple HomePod.

I rarely have a clue what's heading my way until after it has passed by, so I'm always impressed by others who appear to be much better at predictions. Take E. M. Forster, for example. Although he inflicted us with some tortuous tales that make me want to gnash my teeth and rend my garb, he also wrote "The Machine Stops", which was published in 1909. In this tome, Forster predicted globalisation, something we would recognise as the internet, video conferencing and many other aspects of our 21st-century reality.

I have another example that is closer to home for those of us who are bedazzled and beguiled by the combination of artificial intelligence (AI) and mixed reality (MR). The latter encompasses augmented reality (AR), diminished reality (DR), virtual reality (VR) and augmented virtuality (AV).

I'm referring to the short story titled "Norbert and the System" by Timons Esaias. This is a tricky one to track down, but I located it lurking in a secondhand copy of *The Best of Interzone* from 1997, which I snapped up for only 1¢ (plus $3.99 shipping and handling)!

In a crunchy nutshell, our hero Norbert hails from a not-so-distant future in which everyone wears AI-augmented MR headsets. When Norbert starts chatting with a young lady, his AI suggests conversation topics, analyses her reactions and suggests appropriate responses to whatever she says. Meanwhile, her headset is doing the same thing. One way to think about this is that the AIs are having a conversation using their humans as intelligent loudspeakers.

All this makes me think of the reports I've been reading recently about things like researchers in China using AI to monitor people's faces while they are being questioned to determine their level of loyalty to the ruling Chinese Communist Party (CCP). Also, I ran across a paper describing how AI can be used to determine someone's emotional state in around 1.5 seconds by listening to them talk.

It gets better (or worse, depending on your point of view). By observing nonverbal 'tells' like facial expressions, gestures and body posture or position, AI can determine if someone is lying. This is less than good news for certain members of our society, such as politicians, for example.

Interacting with computers

As a research field, human-computer interaction (HCI) focuses on the ways in which people interface with computers. This will become increasingly important when we start to interact with AI-powered robots and the like.

In fact, I'm seeing increasing activity in the field of "social robots". Their task is to provide cognitive stimulation and offer companionship to older citizens who are lonely or in care facilities, especially those with dementia, who keep on asking the same questions and repeatedly saying the same things.

Most of us already have some experience navigating our way through the HCI waters. When we enter a query into an internet search engine like Google, Bing, Ask, or DuckDuckGo, for example, if the results are not what we expect or what we were looking for, we modify our query accordingly.

One of my favorite science fiction authors was Isaac Asimov. Several of Asimov's short stories featured a humongous computer called Multivac. How humongous? Well, in a couple of these tales, we are talking about a machine described in terms of miles, with scientists and technicians scampering through a three-dimensional maze of corridors inside the beast.

We must remember that Asimov wrote these stories at a time when very few people had any idea about computers. All most people knew was that computers were difficult to work with (they didn't have the spiffy voice and graphical interfaces we enjoy today).

This explains why Asimov envisaged a future in which specialists were required to pose questions to Multivac in such a way as to obtain meaningful and useful responses. In fact, several of these stories involve a small cadre of recognised geniuses called "Grand Masters", who have the special insight required to determine the right questions to ask.

Don't prompt me!

Until recently, I thought of Asimov's "Grand Masters" as the stuff of science fiction; then generative AI (GenAI) appeared on the scene. Although its introduction to the public was less than two years ago, almost everyone on the planet is now aware of this technology. Even my 94-year-old mother is conversant with the concept of Chat GPT (which was but the first of many such mega-models), for goodness' sake.

Do you remember the science fiction disaster movie "The Day After Tomorrow"? After it came out, a friend asked, "Have you seen The Day After Tomorrow?" I was honestly able to reply, "Yes, I saw it the day before yesterday" (I'm still chuckling to myself).

I mention this because I recently heard from some folks in Dubai. Referring to themselves as "the metropolis of the day after tomorrow", it seems the folks who don the undergarments of authority there have pledged to train one million people in AI prompting over the next three years.

"What's AI prompting?", I hear you cry. It turns out this really is a thing. Prompts are natural language requests that cause GenAIs to perform specific tasks. Prompt engineering refers to the process by which more meaningful results are achieved by using appropriate formats, phrases, words, and symbols.

Hmmm. Will we eventually require university degrees in prompt engineering to communicate with our AIs? Shades of a Multivac future! **PE**

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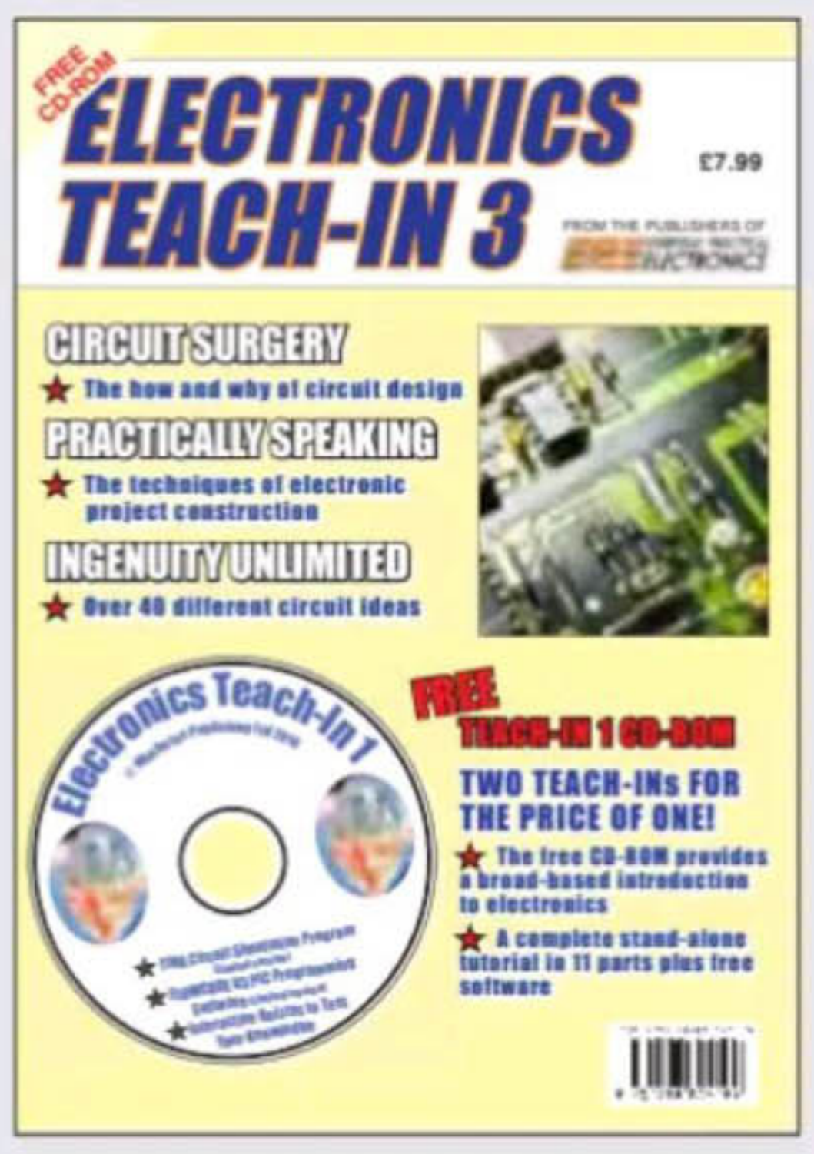

The three sections of the *Teach-In 3* CD-ROM cover a huge range of subjects that will interest everyone involved in electronics – from newcomers to the hobby and students to experienced constructors and professionals.

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Mike & Richard Tooley

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This latest book in our *Teach-In* series will appeal to electronics enthusiasts and computer buffs who want to get to grips with the Raspberry Pi.

Teach-In 6 is for anyone searching for ideas to use their Pi, or who has an idea for a project but doesn't know how to turn it into reality. This book will prove invaluable for anyone fascinated by the revolutionary Pi. It covers:

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- Pi Class
- Python Quickstart
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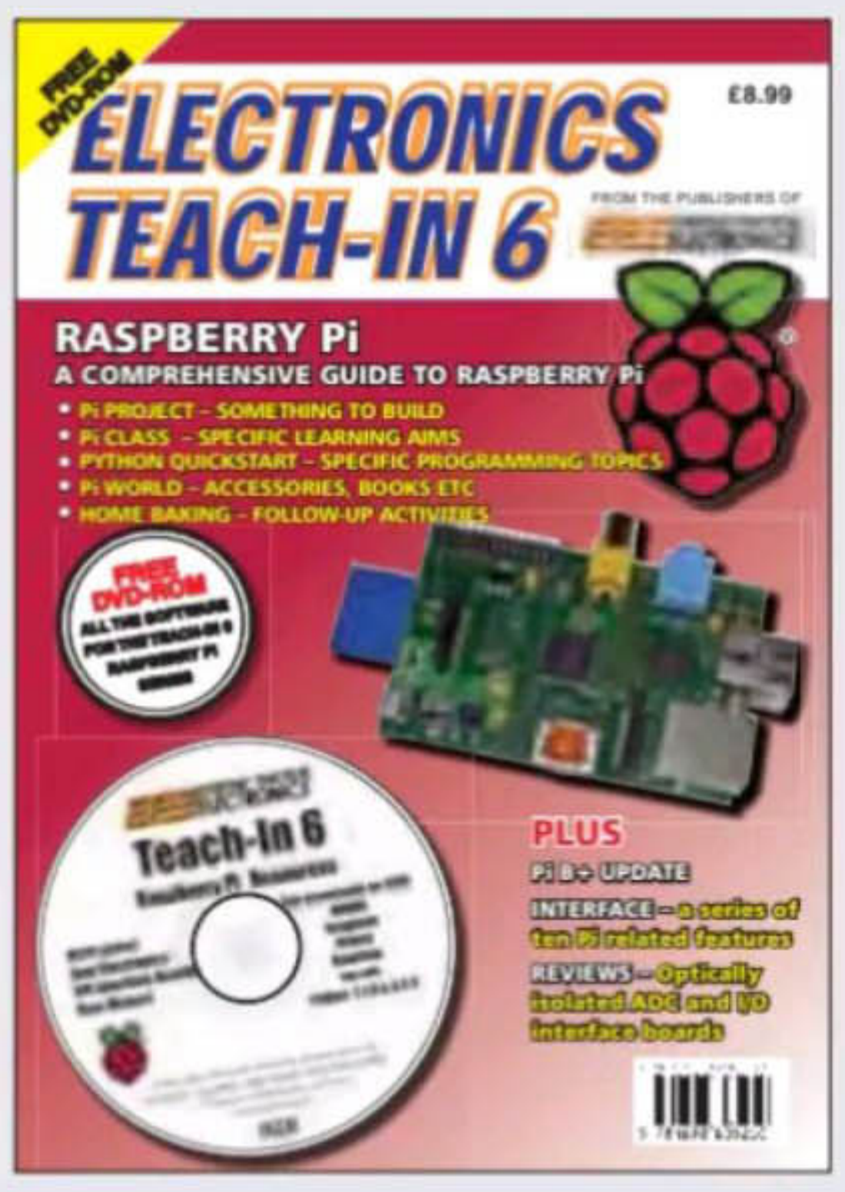
- ...and much more!



The *Teach-In 6* CD-ROM also contains all the necessary software for the series, so that readers and circuit designers can get started quickly and easily with the projects and ideas covered.

ELECTRONICS TEACH-IN 7 – CD-ROM
DISCRETE LINEAR CIRCUIT DESIGN

Mike & Richard Tooley

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PLUS

Audio Out – an analogue expert's take on specialist circuits

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ELECTRONICS TEACH-IN 8 – CD-ROM
INTRODUCING THE ARDUINO

Mike & Richard Tooley

Hardware: learn about components and circuits
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Teach-In 8 is an exciting series designed for electronics enthusiasts who want to get to grips with the inexpensive, popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. It will provide a one-stop source of ideas and practical information.

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This book also includes *PIC n' Mix*: 'PICs and the PICkit 3 – A Beginners guide' by Mike O'Keefe and *Circuit Surgery* by Ian Bell – 'State Machines part 1 and 2'.

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- Lab-Nation Smartscope software.

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The Fox Report

Barry Fox's technology column

Cautionary food for thought

Walk down any street and the chances are you will see a discarded single-use vape. Brightly coloured metal or plastic sticks, these come in a variety of nicotine fruit flavours which youth groups pass round to decide which they like best.

Set aside issues of hygiene and the nicotine addiction issues that this encourages, and spare a thought for the waste. Each colourful vape stick contains a lithium-ion or LiPo (lithium polymer) battery along with a push switch, LED indicator, heater element and small reservoir of the flavoured drug. The batteries are pre-charged re-chargeables, with a standard 3.7V output. They are miniature versions of the larger capacity batteries used in portable devices such as mobile power banks, and they are churned out by the gazillion from Chinese factories: https://pemag.au/l/abyb

Vapes vary, but the basic specification for a LiPo cell will be 3.56/3.7V, with a 400mAh capacity. As the maker's websites may warn, these are 'non-power' cells, originally designed and intended for portable music players, Bluetooth speakers, wireless headsets, GPS trackers, baby monitors, dashcams, pocket games and doorbell devices. They are not intended for use in high-current-drain devices like drones or power tools, although a bunch in parallel will surely pack more punch.

Most important, these batteries are 'dumb' devices, with no charge control – just a positive and negative pair of thin wires soldered to flimsy cell tags. Trying to charge them direct from a DC supply, or shorting the wires, will almost certainly set the cell on fire. Although this very real risk will be well known to our readers, the world at large is generally, blissfully ignorant of lithium battery fire risks. Witness the number of house fires caused by badly designed e-bikes and e-scooters, and their cut-corner chargers.

However, some consumer devices like mobile power banks are designed to work with a dumb battery; the plus/minus flying leads connect to a charge controller combined with in/out USB sockets.

As a test – and one I really do *not* recommend you repeat – I stripped the dumb batteries out of half a dozen discarded vapes, roughly twisted together their positive and negative wires and crudely soldered the twist joints. (My days of fine-point micro-soldering are long gone).

I then de-soldered and removed the single lithium cell from a mobile power bank, of the type now sold for enabling a few calls when the phone battery has gone flat. Finally, I soldered the bunched vape battery wires to the charge controller, adding a simple screw connector for the easy addition of a few more batteries if and when I collect them.

I put the resulting kludge in a glass (non-conducting, non-flammable) container, placed it in the garden well away from the house and connected a low-current USB charger. The controller light first glowed red for 'charging' and later turned green for 'charged'. I connected a mobile phone and it cheerfully signalled that it was charging.

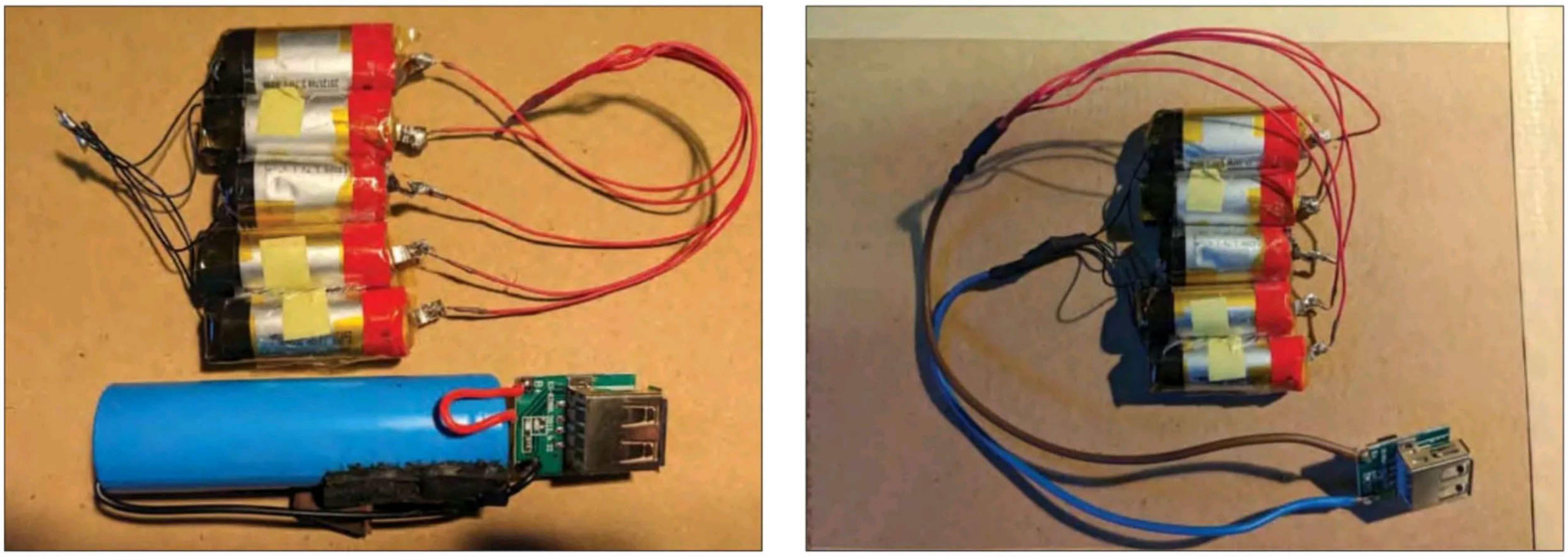
The whole caboodle is now in a halfway-to-good-looking plastic box (a discarded drill bit case) and is currently powering a portable radio designed to run from a phone charger. But it's in a bathroom, close to a window for emergency ejection, and a limitless source of water for dousing.

In reality, my experimental bodge is 'probably' as safe to use as a lot of battery packs now widely on sale, but I'm taking no chances. If you are tempted to exploit the many rechargeable lithium batteries now being discarded, please be similarly careful – work on the assumption that it may catch fire and position it so that this doesn't set fire to your home… seriously.

Meanwhile the fire (and pollution) risk these discards pose when bundled with ordinary house and street waste for landfill doesn't bear thinking about, as this news report shows: https://pemag.au/l/abyc

Words to the wise

Phone theft has now reached epidemic level. Using one on a city street to get directions or take a call has become



(left) Batteries from discarded vapes and a dead battery (blue) with soon-to-be-recycled connector/controller. (right) DIY chargeable recycled vape battery 'power pack'.

My recycled batteries housed in the green case to power a radio. This is **not** safe and such systems should **never** be left unattended where a fire risk may lead to a house fire. Better still, don't repeat my experiment!

risky. Many thefts are 'drive-by'. A thief on a bike races past and grabs. In cafes, thieves distract by waving papers and putting them down over anything valuable on the table. Bags are hooked away from under a seat.

I recently lost my phone. It could have been pick-pocketed or more likely fell out of my pocket when I turned it off for a theatre show and stowed my coat under the seat. I had a spare phone – without a SIM – and making it a fully working replacement was a major pain which taught a lot of lessons, all of which I pass on because at least some may be new and useful to some readers.

The location of Google and Apple phones can in theory be traced with Android/Google and iOS apps. But in practice it's not much help to know that your phone is somewhere inside a scary block of flats. Mine showed as still at the theatre because I'd switched it off inside the theatre; it then disappeared altogether. The theatre 'did not find it'.

Realistically, unless you have lost a phone in a safe place like a friend's house, when a phone's gone, it's gone.

What matters is how easily you can recover from the loss, especially now that so much of modern life is locked to a mobile number, because it is unique to the owner. Apps such as Telegram and WhatsApp depend on mobile phone access – authorising matching apps on a desktop computer needs the phone. NHS appointments and reminders, and travel and event bookings are often attached to the mobile.

You can use Android and iOS apps to make sure contacts stored on the mobile are available from another device, for instance on a home PC – but not so easily available that losing a phone means losing vital security, for example if the phone is in use when stolen. Do remember that some contacts may be stored only on the SIM, unless and until you copy them off the SIM.

You won't appreciate how much you rely on your phone, and the ramifications of losing it, until you have lost it – or set yourself a dummy run challenge.

I store all sensitive data such as passwords with vital digits replaced by asterisks. I also make a hard copy of the data, also with asterisk replacements, and store that in a safe place. Paper can't be hacked, and paper doesn't need a device with a charged battery or mains power, and SIM to read it.

None of this is foolproof. Bletchley Park could have easily cracked the asterisk system. But it buys time and encourages thieves to move onto an easier challenge.

Emails can be accessed by the owner from multiple devices. Voice messages can be remotely accessed by dialling the number and keying in the voicemail PIN. You can also record a new greetings message which advises callers not to send texts to the lost number, and giving an alternative number to call or text.

This is important because I know of no way to read SMS text messages without access to the lost phone SIM.

Don't do as I did and make the mistake of keeping other items – such as emergency money or a travel card – in the phone cover. The travel card can be remotely invalidated and a replacement obtained (at a price and with postal delays) but money is an incentive for a finder to take the money and ditch the phone. Otherwise, they face thanks for finding the phone and then questions on what happened to the cash.

The phone networks have schemes in place to block and replace a lost or stolen SIM. Replacement may take a few days and may cost a few pounds. The networks can also block access to a lost or stolen phone when fitted with a new SIM. Wiping a password-protected phone clean without its passwords should be impossible, but don't underestimate the creativity of the professionals who buy the phones stolen by street opportunists. The remote blocking system uses the phone's 15-digit IMEI (International Mobile Equipment Identity) and may not work in some under-developed countries.

A blocked phone can still be sold for spares, for instance to replace a cracked screen or failed battery.

One practical word of warning. Don't do as I did and take SIM loss and replacement as an ideal opportunity to change tariff or network or both. Changing network while retaining your old number involves use of the PAC (Porting Authorisation Code). The new network cannot do this without the SIM for the old number.

The easiest way is to apply to your existing network for a replacement SIM. This SIM will come with a new number which the existing network will authorise, and then have to switch off and replace with your old number. Then you can progress to getting a PAC and changing network – if you still have the energy left to do anything.

Meanwhile set yourself some golden rules. Carry your phone in a zipped pocket, use it in a doorway or shelter to avoid grab-theft from a racing bike or scooter, and make sure all essential passwords for digital living are easily accessible without your phone and SIM.

All this is much easier to find time for when you have been through the logistic grief of losing a working phone.

Internet radio

While I'm on the subject of phones, here's an idea which may be new to some readers.

Internet radios are pricey, but the function comes free with a smart phone or tablet. Just install an app or browse for the station website.

If you then connect the smart device to an amp and speakers, you have yourself an Internet radio. Some systems will be able to hook up to the phone or tablet by Bluetooth; older systems like hi-fi amps will have an analogue line-input which can connect direct to the headphone socket found on older mobile devices.

It doesn't much matter if the device screen is cracked, as long as it's readable; if the device battery no longer holds much charge, just run it with mains charger. It's no longer a portable device anyway.

This makeshift Internet radio system works a treat – I've done it with phones and tablets, both Android and iOS, connected to a home hi-fi rig.

I needed to do it because modern network/streaming amps have their own inbuilt Internet radio 'tuner', but this may not get some stations you want to hear. Using an external mobile is an easy way to bypass the inbuilt Internet tuner if you want or need to.

Best of all, it's essentially 'free'. PE

Net Work

Alan Winstanley

This month, our Net Work column muses over the impact that artificial intelligence (AI) is having, provides more practical tips for safeguarding online security and protecting data, and provides more news from the space race and the faltering EV market.

The most overused buzzword in technology today must be 'AI'; it seems that every aspect of our lives is becoming 'AI-enabled'. IBM defines artificial intelligence as "technology that enables computers and machines to simulate human intelligence and problem-solving capabilities".

I've heard many a disaffected worker say, "I'm not paid to think", but artificial intelligence systems are actually 'dumb' in the sense that they simply do the job they're designed to do. However, they can also be designed to 'learn' and refine their 'thinking' as they go along.

AI-enabled systems can relieve humans of onerous or potentially dangerous tasks, reduce human errors, vastly increase productivity, or just fob off customers and their tiresome enquiries because not enough human operators are available to answer the phone.

The near-human-like machine performance we encounter daily is fast becoming normalised and accepted by everyday users as though AI really is, well, human. Instead of searching Help files or User Guide PDFs, Windows Copilot, now being introduced in Windows 11 updates, sees Microsoft's next iteration of AI being embedded to help users manage their computers in a far more human-like way.

If I ask Bing Copilot to define, say, medieval etymology using a comic style, the machine results are now indistinguishable from human work: "So next time you're at a Renaissance fair, impress your friends with this tidbit: 'Did you know "medieval" is just fancy talk for "middle age"? Pass me another turkey leg, good sir!'".

More mundane tasks, such as summarising real-life Amazon product reviews for buyers, analysing – not always correctly – dodgy Facebook posts, or describing items for sale on eBay, have fallen under the spell of AI-powered 'bots as well.

So-called 'generative' artificial intelligence (GenAI) goes further by using advanced routines, machine learning and algorithms to create pseudo-authoritative, real-time responses to our queries, online search terms or smart-speaker commands. This is seriously affecting regular news channels, whose online content is being scraped wholesale by GenAI 'bots looking to re-publish the latest news for themselves.

In turn, local news journalism and news-gathering are suffering from a triple-whammy: competing against generative news content scraped online, social media (worryingly, people really do turn to TikTok for their 'news') and the slump in traditional advertising revenue.

Flaming hot dogs

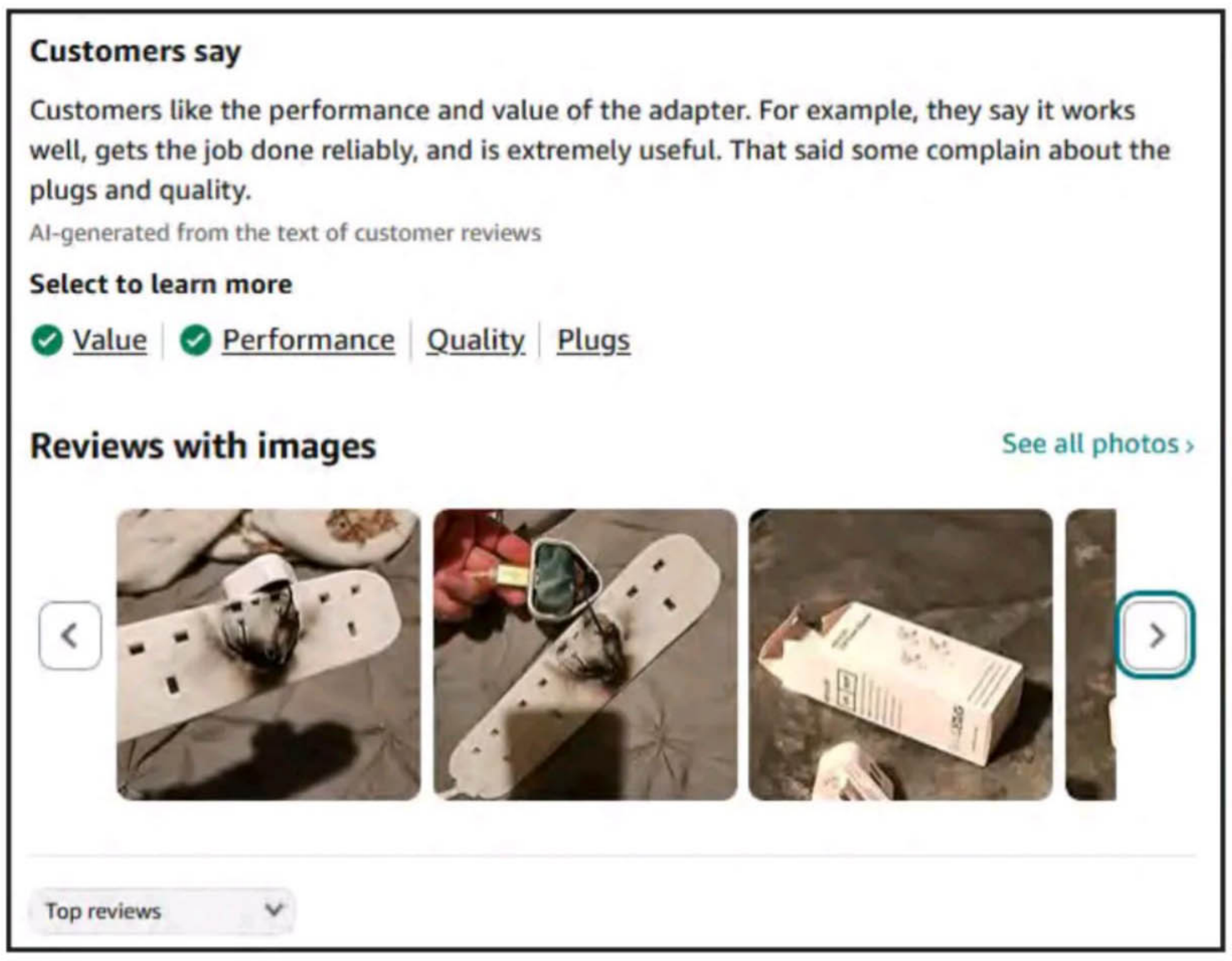
Enormous advances in technology, electronics, mechatronics and coding are also making AI-powered robots and drones a reality. China has reportedly produced squads of robotic quadrupeds that could be armed with rifles, while in contrast, the American-made 'Thermonator' quadruped packs a handy flamethrower that is said to be legal in most USA states but probably nowhere else. You can see them in action on YouTube at **https://youtu.be/xEVwkzAcqOQ**

These 'robo-dogs' doubtless have many potential peace-time roles, but I guess it's only a matter of time before autonomous machines like these could operate in swarms under combat conditions. There's a cheery thought!

'Kamikaze drones' are already being used in combat by Ukraine, with AI-powered seekers that allow them to guide themselves to a target their operator selects, even if their comms are jammed or lost (**https://pemag.au/link/abyh**). How long before an AI-equipped drone can simply be unleashed to 'seek and destroy'?

The darker side of AI is seen in the production of deepfake videos or, as I found out myself, the pirating and re-copying of textbooks under other titles to cash in on the original work (see *Net Work*, May 2024).

It is still going on now; you can search Amazon for niche subjects such as

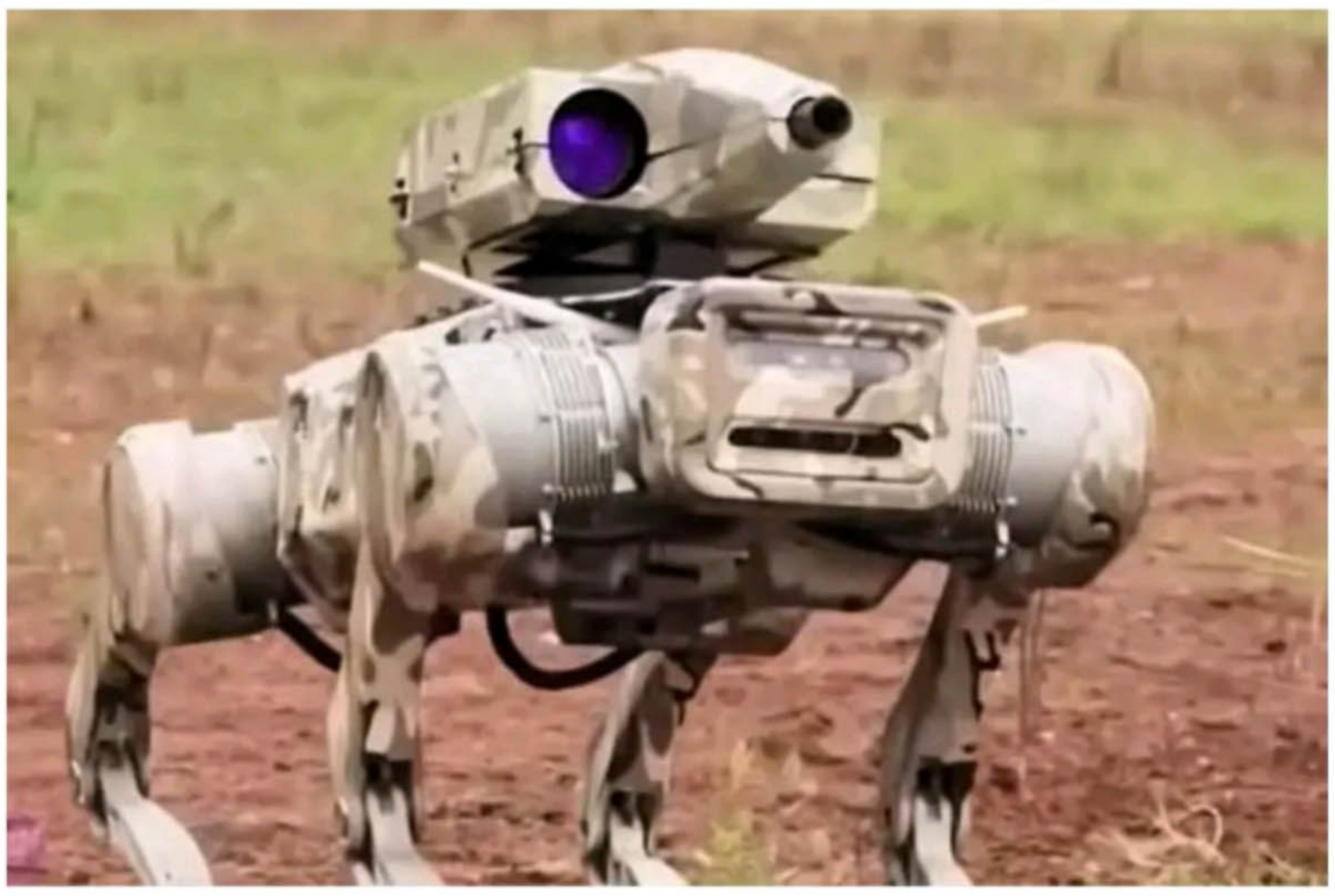


Customers say

Customers like the performance and value of the adapter. For example, they say it works well, gets the job done reliably, and is extremely useful. That said some complain about the plugs and quality.

AI-generated from the text of customer reviews

AI is used to summarise product reviews submitted by Amazon customers. It had mixed thoughts about this smoking mains-powered USB charger! (Source: Amazon UK)



A cross-haired terror: China's PLA is developing armed quadrupeds that are not exactly cute or house-trained. (Youtube/@carrosshow9598)

The US-made Thermonator is the world's first flame-throwing robot quadruped, intended for agriculture, ice clearing and similar uses. Any similarity to the word "Terminator" is purely coincidental! (https://throwflame.com)

"Master R Programming" or "DIY Lithium Batteries Handbook", for example, to see a wide variety of similar book covers complete with pseudonyms. You would never know they were all generated by AI before being polished off and uploaded using cheap labour. Established authors are also suffering from the curse of foreign AI-generated books being published using their names.

All this AI-enabled computing needs far more 'juice', and new data centres are needed to provide the raw data processing power, such as the proposed 185-acre AI data site mentioned in July's *Net Work*, destined to be one of Europe's largest.

The personal computer industry is also eagerly cashing in on the AI wave, with the latest tranche of 'AI PCs', designed to give Windows Copilot and AI-based apps more headroom to play with. Hence, the term NPU (Neural Processing Unit) now appearing in PC sales blurbs; an integrated processor optimised for data-driven AI-related tasks.

A blog entry by computer maker Dell reckons that "the advances from Generative AI will compare to the PC's introduction 40 years ago, which brought unseen levels of productivity to the world… This [AI] will require you to reimagine how you work with the familiar laptop and desktop of today".

Dell foresees new ways of interacting with technology, including using voice, gestures or visual commands, stating, "Your PC experience will transition from searching to prompting, from reading to understanding, from editing to directing." The days of pressing F1 for Help are fast disappearing, and AIs like Copilot will do more of the thinking and heavy lifting for you.

Remain vigilant

Last month's column discussed many security-related concerns that can affect everyday Internet users. I wrote that using passwords to log into websites is becoming increasingly insecure, mainly due to the risk of them falling into the wrong hands or being too easy to guess.

I recently noted how even the UK's National Lottery website, with a EuroMillions rollover prize of some £130 million (€153 million or AUD 247 million!) at stake last month, simply needs an ordinary username/ password combo with no other authentication being required. Hopefully, checking the lottery winner's ID will be more rigorous! (Even that can go wrong, as demonstrated in the famous BBC Guy Goma/Guy Kewney TV interview identity mix-up at **https://youtu.be/e6Y2uQn_wvc**).

While any password can theoretically be 'cracked', starting with brute force dictionary attacks, using a string of, say, three English words as a password offers a good balance between security and ease of use.

Anyone dealing with valuable property transactions, such as a house, antique or car purchase, by email should also be wary of fraudsters getting in on the act. It's extremely rare, but it happens; a crook may intercept email communications – perhaps starting weeks earlier – and impersonate the genuine party, but slightly changing a domain name for a similar-looking one, maybe replacing the letter 'l' with a digit '1' or a zero '0' in place of a letter 'O'.

An email from **conveyancing@myso1icitor.co.uk** could easily fool a busy or stressed-out person. The rule is to be very vigilant and trust your instincts. Does something pass the 'sniff test'? When there's any doubt, a golden rule is to phone the party directly on a pre-established number and confirm the situation first.

The idea of Two-Factor Authentication (2FA) to send a One-Time Password (OTP) to a mobile phone is intended to enhance security. In a scam known as 'SIM swapping', fraudsters try to transfer the victim's mobile phone number to another phone to intercept those One-Time Passwords. Network operators have been working hard to overcome this, and London's Metropolitan Police offers some basic advice (PDF) for users at **https://pemag.au/link/abyi**

Some users dedicate a second mobile phone to receiving 2FA texts rather than using their main one with a widely known number, but the consensus is that using a physical hardware key or an authentication app with biometrics is far more secure than relying on 2FA.

Last month, I showed some USB security keys made by Yubico, and the independent Techradar website recently reviewed several software apps and recommendations, including Authenticator by 2Stable, NordPass and Authy, with Google Authenticator classed as a basic, free app. You can learn more at **https://www.techradar.com/best/best-authenticator-apps**

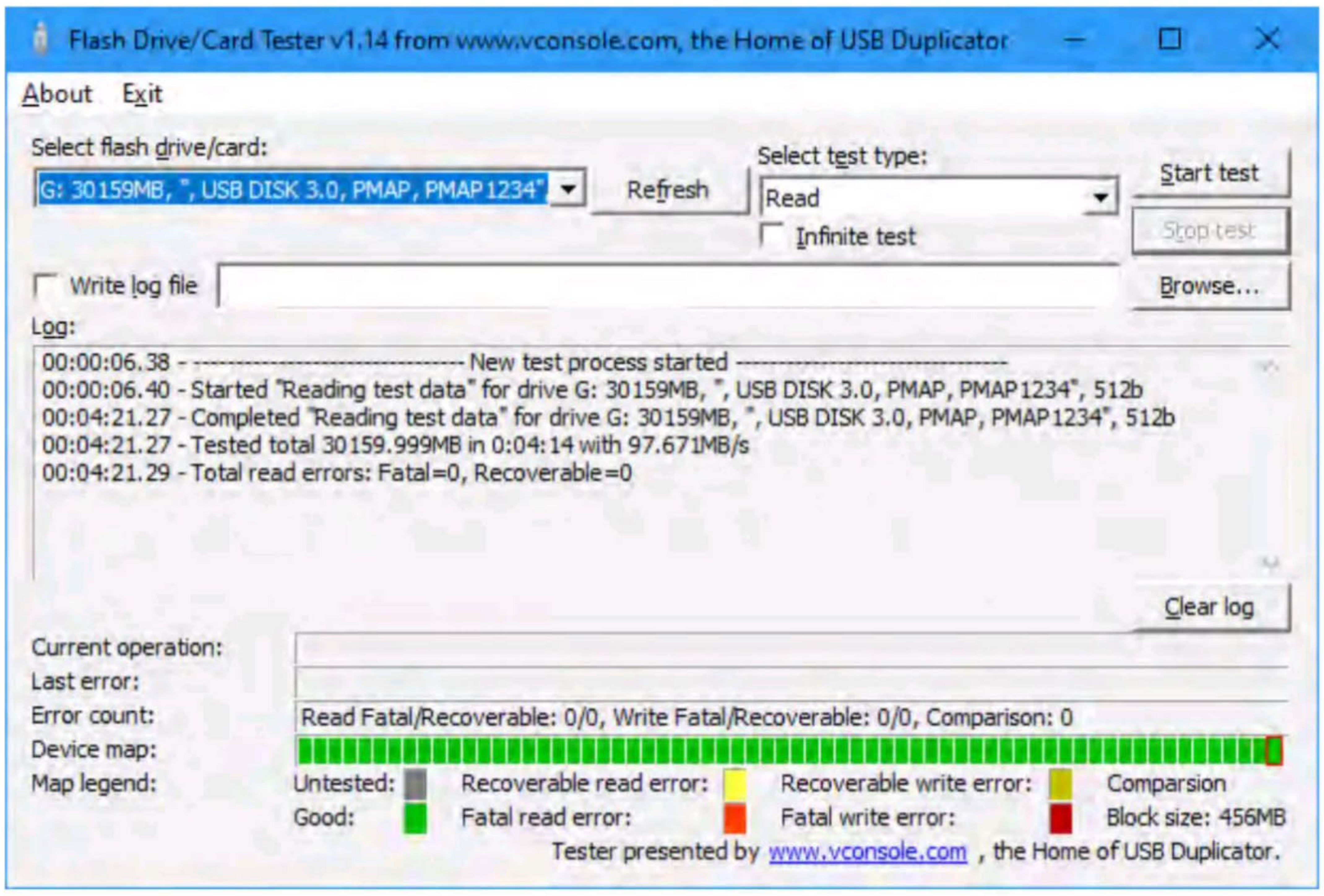
Save it securely

Still on the subject of USB devices, someone once berated me online when I described a 64GB USB flash drive as being "modern". My online accuser scoffed and claimed that 1TB is now the norm. I doubted whether users needed that sort of capacity for their everyday needs unless they handle media files. Still, if I have to store sizeable volumes of data, I use a Samsung Portable SSD, which is far more robust and ESD-shielded than any USB flash drive will be.

I'll maybe take an air-gapped 'backup of last resort' for archiving, using standard 3½-inch (PC desktop-size) 1TB+ hard disks stored in rigid plastic cases, accessed using a quality StarTech hard disk docking station. Of course, many users pay for online cloud storage

SAMSUNG
Portable SSD T5
Samsung Portable SSD

Samsung Portable Solid State Drives (SSDs) are more robust than USB flash drives and are probably a better bet for longer-term data storage.


Flash Drive/Card Tester v1.14 from www.vconsole.com, the Home of USB Duplicator
About
Exit
Refresh
Start test
Stop test
Browse...
Clear log

Select flash drive/card: G: 30159MB, ", USB DISK 3.0, PMAP, PMAP1234"

Select test type: Read

☐ Infinite test

☐ Write log file

Log:

```
00:00:06.38 - ------------------------------ New test process started ------------------------------
00:00:06.40 - Started "Reading test data" for drive G: 30159MB, ", USB DISK 3.0, PMAP, PMAP1234", 512b
00:04:21.27 - Completed "Reading test data" for drive G: 30159MB, ", USB DISK 3.0, PMAP, PMAP1234", 512b
00:04:21.27 - Tested total 30159.999MB in 0:04:14 with 97.671MB/s
00:04:21.29 - Total read errors: Fatal=0, Recoverable=0
```

Current operation:

Last error:

Error count: Read Fatal/Recoverable: 0/0, Write Fatal/Recoverable: 0/0, Comparison: 0

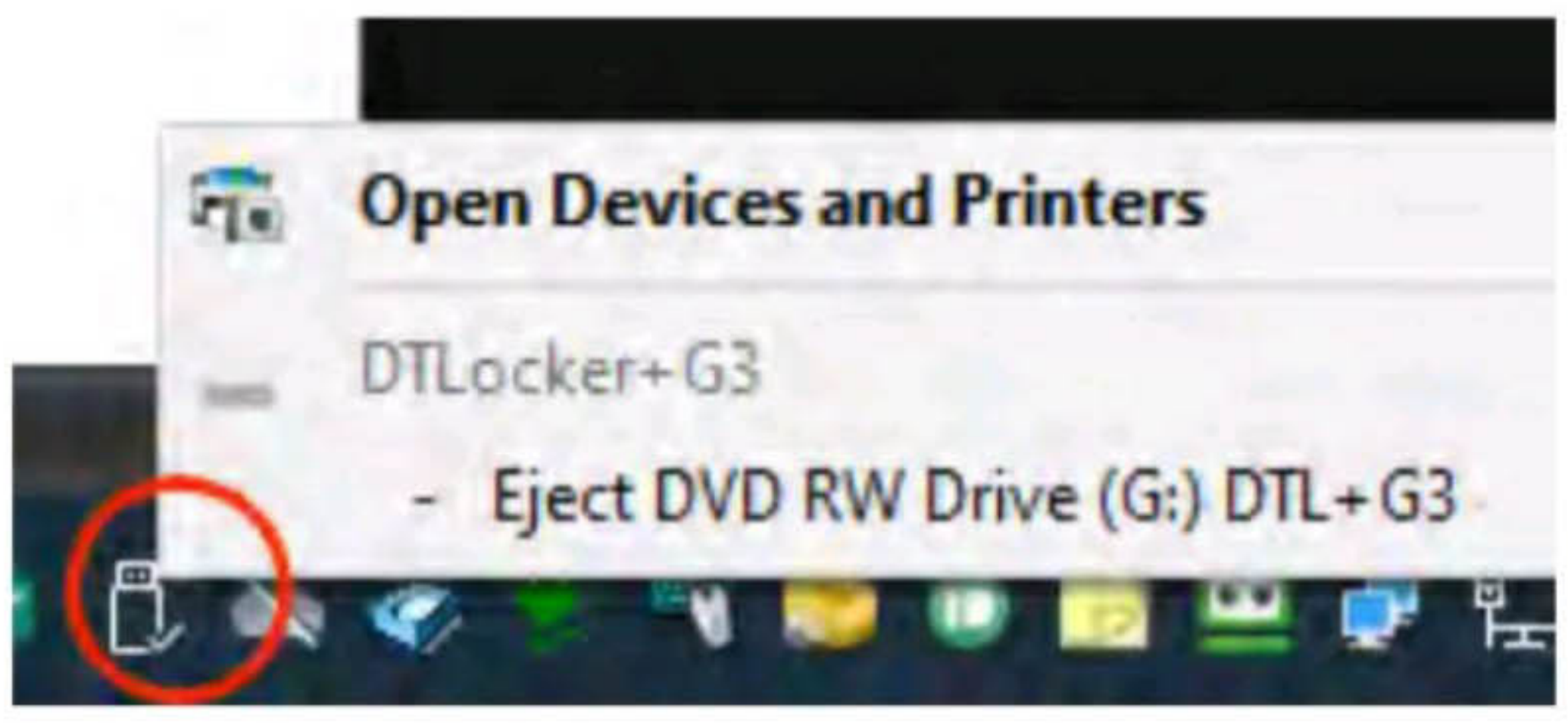
Device map:

Map legend: Untested: ■ Recoverable read error: 🟨 Recoverable write error: 🟨 Comparsion

Good: 🟩 Fatal read error: 🟥 Fatal write error: 🟥 Block size: 456MB

Tester presented by www.vconsole.com , the Home of USB Duplicator.

This Flash Drive/Card Tester software will check the read/write performance of USB memory and flag any hardware errors it finds.



Using the Safely Remove Hardware and Eject Media icon will avoid data corruption when removing USB drives.

instead, but it can be slow and pricey (and possibly also insecure).

There are plenty of USB flash drives to choose from, and I sometimes buy a pack of 32GB or 64GB flash drives, always from a reputable brand such as Integral, Verbatim, SanDisk or Kingston, to share files between PCs or hand them out to coworkers, friends or family. I avoid buying anonymous or oddly-branded ones as they may fail without warning or they might even have fake capacities (something that co-writer Barry Fox covered in March 2021).

I have also seen some very convincing counterfeits of genuine products. Readers might like to try the Fake Flash Test program (from **https://pemag.au/link/abyj**), which can check the drive's capacity. There's also the USB Flash Drive Tester from Virtual Console, downloadable for free from **https://www.vconsole.com/download**

Remember to run these Windows programs in Administrator mode, or they won't work.

Integral 'Neon' drives are cheap and cheerful, for tossing around the desktop, and the Integral 'Fusion' range has a tiny form factor and metal casing, which I use for playing MP3s in the car – equivalent to holding 50 or 100 CDs worth of music tracks on something not much bigger than a thumbnail!

Most, but not all, flash drives have an LED activity light, so avoid unplugging them when the light is flickering, as data could be corrupted. The best way to remove them in Windows is to click the 'Safely Remove Hardware and Eject Media' icon in the system tray (although, from Windows 10 onward, you should be able to safely unplug them after activity stops).

Sometimes you might have personal data or computer files that you want to keep safe and secure, away from prying eyes. One way is to use an encrypted USB flash drive that can only be accessed by the authorised user. They may require a PIN to access them, while some may use biometrics, such as the fingerprint reader used in the Lexar JumpDrive Fingerprint range.

The Datashur USB range by the specialist UK company iStorage includes high-security and high-end encrypted USB keys, starting at about £40 for a 4GB version (32GB maximum). It works on any operating system and encrypts data at hardware level. A small keypad captures a 7- to 15-digit user PIN, and after 10 failed attempts, the PIN is deleted, although access can still be granted with a second 'Admin' PIN.

The metal-bodied USB 2.0 device has an IP57 rating. The advanced DataShur BT uses smartphone biometrics to access it, noting that ten failed logins cause a total device reset. Retail prices start at £55 + VAT for 16GB, although my more affluent online opponent might like a 1TB version with a keypad and 1TB microSD slot instead for a mere £720!

Some of the iStorage range is listed on Amazon, or you can buy direct from the UK supplier, including bulk and customised versions of the devices, at **https://istorage-uk.com**

With a more modest budget in mind, I keep in my briefcase a legacy Kingston DataTraveler Locker+, a tough metal-clad, hardware-encrypted USB key that requires a PIN before a secure drive letter can be accessed. A PIN screen prompt and 'lost and found' contact details are available to users.

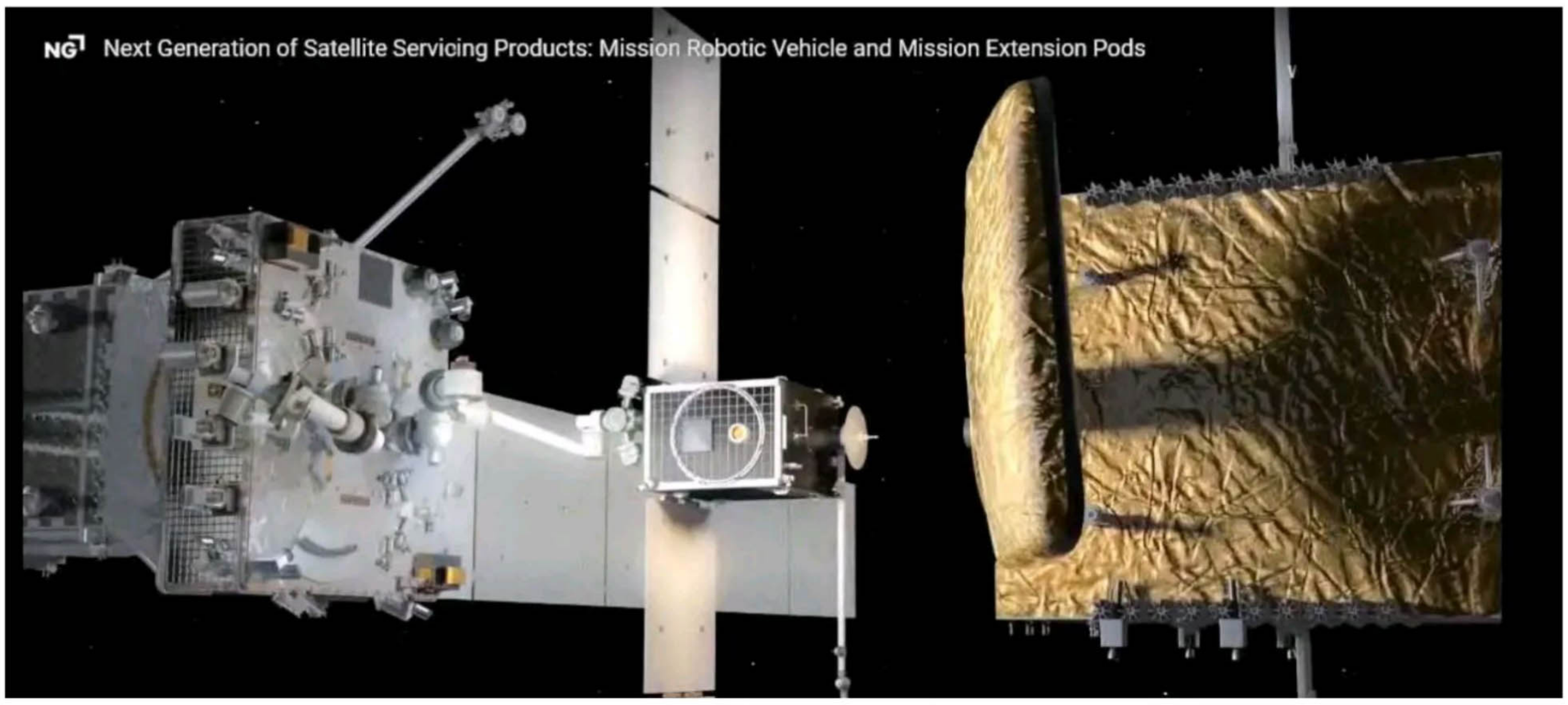
The latest IronKey Locker versions also have an Admin override and USB-to-cloud backup. However, I have mixed feelings about relying on cloud services, as history proves that

16GB
DataTraveler
LOCKER+ G3

The Kingston DataTraveler Locker+ G3 is a lower-cost encrypted USB flash drive; IronKey Locker is the latest version.

Integral's Neon USB flash drives are cheap and cheerful; the tiny Fusion is aluminium-clad for ruggedness.

The iStorage Datashur is a high-grade PIN-protected USB flash drive for storing data securely.


NG Next Generation of Satellite Servicing Products: Mission Robotic Vehicle and Mission Extension Pods

In-flight refuelling: Grumman's Mission Robotic Vehicle (left) would use a robotic arm to fit a Mission Extension Pod (centre) onto a customer's satellite before sending it on its way again.

such third-party vendors are prone to discontinue services at short notice.

Their Amazon prices currently start at £30, or you can learn more about the devices or buy direct from Kingston at https://pemag.au/link/abyk

If all you want to do is encrypt data on any form of removable media (USB, CF, SD etc), Virtual Console offers AES-256 Encryption software for USB flash drives for $15.00 per licence. You can download it from the website https://www.vconsole.com/download although I have not personally tried it.

Space News

This month's news of the space race starts with China's success in returning two kilograms of soil samples from the far side of the moon, a world first. A YouTube video documentary at https://youtu.be/cTqvz7Qtd2o (there are others available) showcased the 'unboxing' of the returned capsule.

China has offered to share samples with the international scientific community, but America's Wolf Amendment legislation raises questions over whether NASA can cooperate with China this way. Apollo's manned moon missions obtained a total of 382kg of moon soil and rocks, starting in 1969 when Apollo 11 returned 21.5kg to Earth, the first soil collected from any celestial body. You can take a virtual tour of NASA's sample lab at https://curator.jsc.nasa.gov/lunar/index.cfm

The spacenews.com website points to China's recent application to create a 10,000 satellite constellation called HONGHU-3. China is also investing heavily in SpaceX-style re-usable rocket launches; a carrier rocket successfully completed a 10km VTOL flight test in northwest China in early July, and a larger version is set to launch in 2025.

Earlier, a ground test of a privately produced Tianlong-3 VTOL rocket went awry when the rocket broke away from its moorings and launched into the air before crashing again in a huge fireball (shown in the BBC video at https://pemag.au/link/abyl).

The direction of travel (into orbit) is clear; coupled with several earlier mysterious satellite launches, there are major concerns that China is constructing an advanced surveillance network that could eventually track and take high-resolution photos or videos of anything in the Indo-Pacific region.

Meanwhile, Boeing's maiden voyage of the Starliner crew capsule is now into extra time. The June 5th launch to the ISS was intended to last about a week, but problems with thrusters and minor helium leaks are causing flight engineers to cautiously extend the mission to 45 or even 90 days onboard the ISS while risks are assessed. There are no reports of any other problems, including with power or food.

Four years ago in *Net Work*, June 2020, I reported on the Grumman Mission Extension Vehicle (MEV), a space tow truck that can physically dock with orbiting satellites running low on fuel to extend their working life. The vehicle is compatible with 80% of orbiting geostationary satellites.

Grumman has plans for a next-generation space breakdown truck: a proposed Mission Robotic Vehicle (MRV) will use a robotic arm to dock with a client's spacecraft, providing robotic inspection, relocation, repair, debris removal and filling up. Mission Extension Pods (MEPs) could also be applied to extend life up to six more years. How Grumman expects the in-flight refuelling service to work is shown at https://youtu.be/hieqTEaEBQo

The NASA spacecraft Voyager 1 and Voyager 2, launched 46 years ago in 1977, are now the only craft to fly in interstellar space. The current status of these truly remarkable vehicles can be tracked at https://voyager.jpl.nasa.gov/mission/status/

The Voyager program was led by NASA/ JPL scientist Ed Stone, who passed away on June 9th this year. JPL pays a fitting tribute at https://pemag.au/link/abyn

EVs: static electricity

Recently, I saw a BYD electric car making its way silently through my rural village, a sure sign that the Chinese EV onslaught is edging ever closer. The EV market continues to falter, though, as high purchase prices, poor residuals, the usual worries about range anxiety and a patchy charging network dampen demand for these expensive new vehicles. Remember that the UK has even failed so far to roll out a dependable national smart meter network!

The bulk of EV sales now go to fleet buyers. Owners also face intense insurance and repair problems, and trade wars may yet break out with US and EU tariffs threatening to curb demand even more.

In January 2022, I featured the GWM Ora, a cute, chic-looking EV made by China's Great Wall Motors that was undergoing type approval for UK sales. So far this year, fewer than 900 Ora cars (0.9% of all YTD sales) have been sold in Britain, and Great Wall is now closing its European HQ in Munich at the end of August due to poor sales.

The EV market's woes don't end there. After managing just 259 UK sales of their £36,000 cars, Fisker, an EV start-up whose stylish 'Fisker Ocean' came with 'green' credentials (see *Net Work*, May 2022), has filed for bankruptcy. Bloomberg reports on the sorry tale at https://pemag.au/link/abym

Perhaps that same *Net Work* column was jinxed, as the promising ZipCharge Go 'powerbank for EVs' that I also showed never got beyond the prototype stage, nor was there any sign of electric trucks being trialled on my local motorway either.

There's some better news from Britain's electricity generation network. The Electricity System Operator (ESO) expects it will have more 'headroom' to cope with contingencies this coming winter compared with last year.

The role of Demand-Side Response

is to balance electricity supply with demand, and the ‘Demand Flexibility Service’ was created urgently following the Ukraine energy crisis to incentivise consumers by offering them a modest cash inducement to reduce their power usage.

It worked; during the crucial winter period of 2022/23, 1.6 million households and businesses participated in the service by shifting demand, saving over 3300MWh of electricity, says the ESO, and in winter 2023/24, 2.6 million users saved over 3700MWh.

The ESO has now confirmed there will be no need for the Demand Flexibility Service during the coming winter 2024/25 period. Still, they intend to develop the concept as a commercial service throughout the coming year and encourage users to habitually economise as a matter of course.

The energy providers are also incorporating state-of-the-art battery energy storage systems (BESS) into their networks to provide backup energy sourced from renewables. One example is Tesla’s Megapack, which offers pre-manufactured 3.9MWh battery packs off-the-shelf.

These are already being used in Europe’s largest battery storage farm in Cottingham, England, a project that has reportedly taken seven years to complete. Other redundant sites are also being given over to battery farms.

If we think we have problems in the UK with planning permission, Australia’s Victorian Government commissioned a Tesla BESS farm for its Victorian Big Battery (VBB), treading carefully on hallowed ground to respect the Wadawurrung people, traditional owners of the land on which VBB operates, they are at pains to acknowledge.

During commissioning in July 2021, a liquid coolant leak caused electrical arcing, with one of the battery packs ‘failing safe’ after catching fire. As regular *Net Work* readers will know, Li-Ion batteries can thermally run away and cannot readily be extinguished. So, Tesla’s advice was to let it burn itself out over six hours, which it did, incident reports state. Normal operation was then resumed.

Next month

That’s all for this month. From the next issue, I’ll be at the wheel of a shorter *Net Work* (steering?) column, as after 28 years and half a million words, I’m easing off the accelerator in the hope that regenerative braking will recharge my ageing batteries!

Practical Electronics will also reach another milestone in the forthcoming November issue, but I’ll bring more news about that next month!

In the meantime, the author can be reached via email at: alan@epemag.net PE

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Constructional Project

Build a low-cost, calibrated MEASUREMENT MICROPHONE

If you have ever wanted to characterise or build loudspeakers but couldn't justify the cost of a fancy microphone, or you want several microphones you can tailor for performance or recording, this project is for you. It's a phantom-powered, balanced, calibrated microphone you can build for much less money than a commercial equivalent.

Project by Phil Prosser

This project aims to build a low-cost measurement microphone using an inexpensive electret condenser microphone (ECM) and a few other bits and pieces. The WM61A and alternative ECM capsules listed below are only a few dollars each. If you recycle parts for the housing, you can make a good microphone for under £20, which is ideal for getting started.

With the calibration files we provide, it will let you measure frequency response to within about ±2dB from 20Hz to 20kHz.

This Microphone uses phantom power, where the power for the microphone is provided over the signal lines from your microphone preamplifier or mixer. Most commercial microphone preamps can provide this, along with many similar DIY designs (including my Loudspeaker Testing Jig, published in the June 2024 issue). This avoids the need for batteries and is widely supported.

If you want to build this as a measurement microphone, plenty of ECM capsules with calibration files are available from the Silicon Chip Online Shop at a modest cost. The capsules are numbered and you just need to match up your number with the downloaded file to get accurate calibration data for that capsule.

We also have instructions to tailor the frequency response of a microphone for vocal or instrumental use.

Aiming for a flat response

How well does it work? Fig.1 compares the raw performance of two £1 WM61A capsules to our reference Dayton EMM-6 microphone. This is before the application of the calibration file. The curves' 10-12dB offset is simply due to these capsules being more efficient than the EMM-6; note how the responses barely go outside the 9-11dB/11-13dB ranges that represent ±1dB from the average.

To achieve this comparison, we placed the microphones within a couple of millimetres of the same point as the reference microphone. We feel the performance shown is pretty good for such a simple and low-cost design.

As mentioned earlier, the capsules we're offering come with calibration data that allows the 1-2dB error to be corrected. The calibration accuracy is limited by our Dayton reference microphone, although we are confident that above 50Hz, it is flat within a couple of decibels.

A Behringer ECM8000 runs about £40, while the Dayton EMM-6 starts at around £70. As mentioned earlier, you can probably build the Microphone described here for around £20, possibly a bit less.

Note that the ECM8000 doesn't come with a calibration file, while this one does, making it even better value. So you can achieve pretty good performance at a very competitive cost with this project.

To get the best from your Microphone, the design incorporates a phantom-powered preamp and a balanced output buffer based on an industry-standard design, the 'Schoeps transformerless design'. This harks back to

JLI60A V02 sn002
A2K2
BJ SN00
KECH2742 8N2 GAIN 3K9 6N8 ATT
PRIMO EM258 sn02

Here's a collection of the types of Measurement Microphones you can build.

The Panasonic WM-61A microphone.

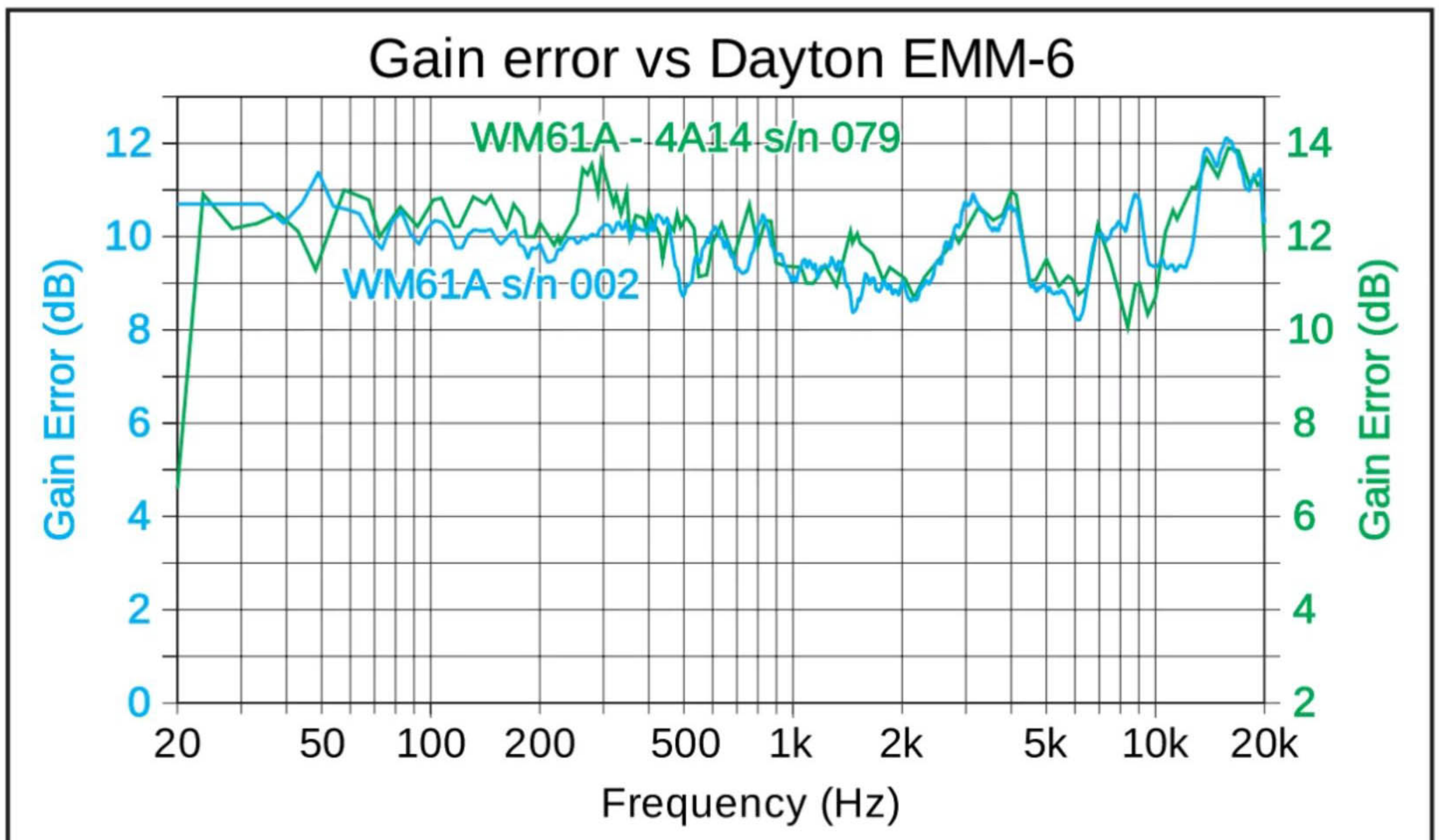


Fig.1: a comparison of the performance of two of the £1 WM61A microphones capsules to our reference Dayton EMM-6. This is uncalibrated performance; we can supply ECM capsules with calibration files that will reduce these errors. The offset of about 10dB/12dB for the two samples means those capsules are significantly more sensitive than the Dayton EMM-6, which is rated at -40.3dBV/Pa.

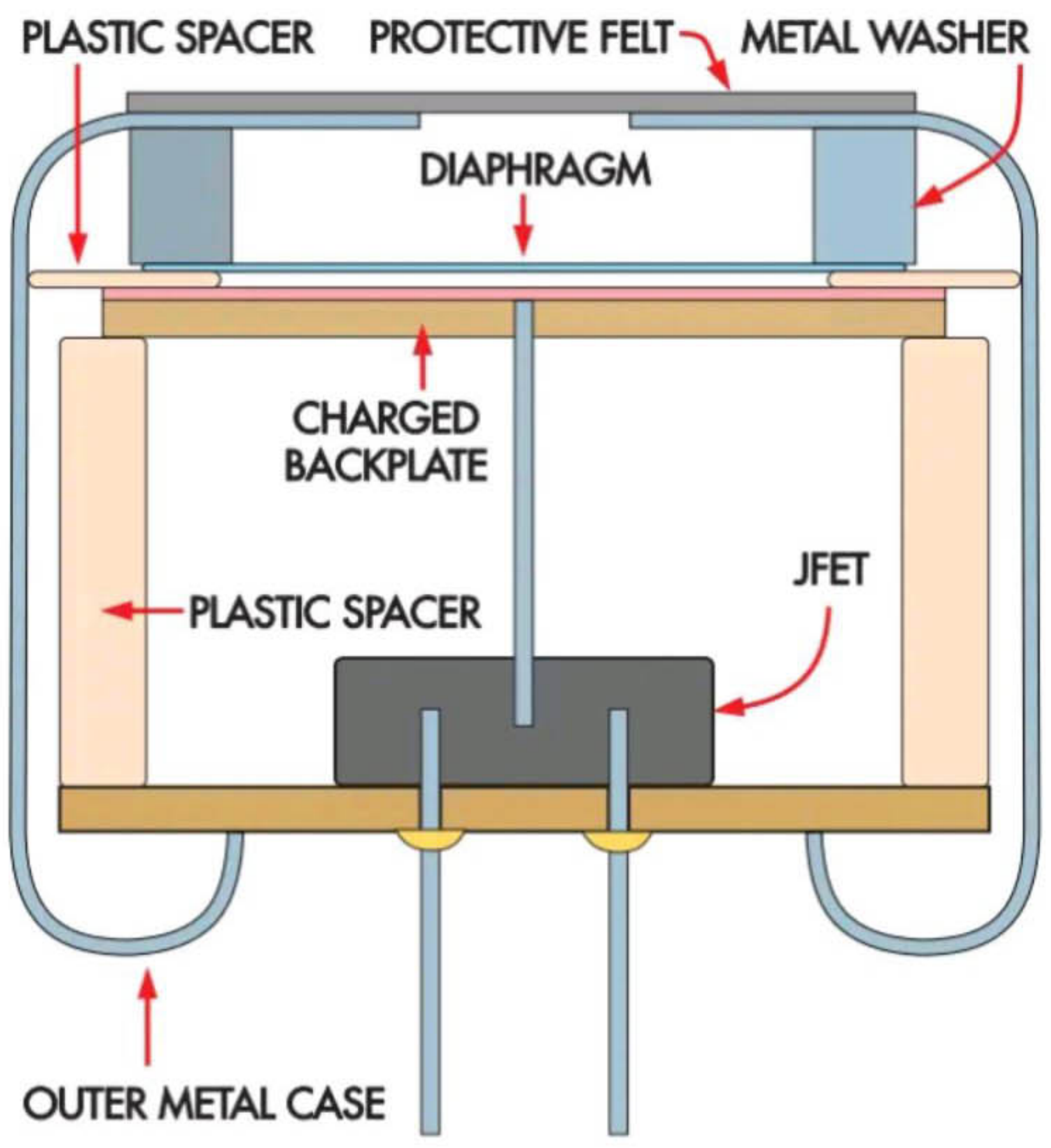


Fig.2: the structure of an electret condenser microphone (ECM). The internal FET amplifies the small AC voltage generated by the diaphragm moving in relation to the charged backplate.

the 1960s and is used in a vast range of professional and measurement microphones. We have added an input and filtering section to suit the ECM capsules we present here.

The design is quite conventional, so you can make a general purpose phantom powered electret condenser microphone using this project. As you will see later, we have included the ability to tune the Microphone's response.

In our application, this is to get a flat response, but nothing is stopping you from using that capability to adjust the microphone response to suit vocals or instruments.

So, how can you really get a good electret microphone for two bucks? ECMs are very simple devices and are made in huge volumes. As shown in Fig.2, they work by sound moving a very thin diaphragm relative to a backplate that is connected (typically) to the gate of a FET. A charge is created between these, and the capacitance between the diaphragm and backplate changes as the sound moves the diaphragm.

The formula is $C = \varepsilon_0 \times A \div d$, where d is the separation between the diaphragm and the backplate, A is the area of the plate and ε_0 is a mathematical constant. The charge between the plates Q is constant, and since $C = Q \div V$, as the capacitance changes due to the sound, so does the voltage between them (V). This drives the FET.

As the capsules are tiny, and the diaphragm extremely light, these devices can have excellent frequency response to very high frequencies with little resonance.

The Panasonic WM-60A and WM-61A microphones are legendary examples and have an exceptionally usable frequency response from 20Hz to 20kHz. In the past, they were the mainstay of DIY measurement microphones. They were a workhorse component used in a wide range of devices, including telephones, which meant they were made by the million and thus cheap.

Panasonic stopped making these in the early 2000s, which some ascribe to the demise of the old-fashioned 'phone. Panasonic capsules can still be found, but many sellers list generic 6mm capsules as WM-61As. We bought a large quantity of real 'new old stock' (NOS) parts, all from a single batch, measured their response, and are offering them for sale – see Table 1.

Before we found a batch of old stock WM61As, we bought and tested a huge number of microphone capsules. Our experience has been that ECM capsules that are 'flat' to 20kHz tend to be 6mm diameter units; they are pretty small. The larger 10mm ones generally exhibit a significant peak in the response between 5kHz and 10kHz, making them less than ideal for measurement applications.

Therefore, all our recommended ECM capsules are 6mm. We also learned that the majority of capsules available cannot be used in this project as they exhibit peaks or dips, many over 10dB, that we are not comfortable addressing by calibration.

Virtually all the satisfactory mics we found will be available from the Silicon Chip Online Shop, including the required SMD calibration components, all for similar prices.

Another thing we learned is that there is no ideal ECM capsule that will give acceptable performance without calibration or at least some equalisation of the native response of the capsule. The old Panasonic WM61A capsules tend to be more consistent than most modern alternatives, but there can still be significant differences in frequency response from batch to batch.

Manufacturers present typical frequency response plots for their ECMs, but there is significant variability in their response above 10kHz between batches.

The Primo EM258 capsules are excellent, but at £6.10 plus shipping, they are starting to defeat our goal of a low-cost design.

We eventually concluded that calibration of each ECM capsule is essential. So we have done a couple of things:

- We designed a circuit that allows you to add a peak or dip and either a ramp up or down to the frequency response. We have determined the required combination for each type of ECM we tested to get a reasonably flat response.

- Each ECM capsule we supply has a serial number matching a set of calibration corrections to make it perform even better than just with the frequency response adjustment. The calibration file can be loaded into the Room Equalisation Wizard (REW) or Speaker Workshop software to get your measurements as close as possible to ideal.

For those who want to build a vocal or instrument microphone, we will show you how to tune the circuit's response to get the 'colour' you want in the microphone you build. If you are making a vocal microphone, you don't need one of the calibrated ECM capsules from our store; you can save money by buying a similar one from an internet vendor.

Which capsule do we prefer? The NOS Panasonic devices still stand out. The best still-officially-available type is the Primo device. The CMC-2742PBJ-A is pretty good with compensation (and still available). With compensation, all the types we're selling are within a decibel or so of our reference mic to at least 10kHz, and with calibration, will be within ±2dB (or better) of our reference mic.

Performance

We are proud of the performance achieved, especially in a low-cost project. Fig.3 shows the compensated (but not calibrated) frequency response of 10 of the ECM capsules we tested. Some things we noticed are:

- The CMC6027-24T family of devices are very sensitive. That could be beneficial under certain circumstances, but using these for very close measurements or in very loud settings will result in potential compression and distortion.
- All microphones are within ±3dB of their average before the application of calibration over the range of 50Hz-20kHz
- All are pretty flat through the region where you would put a bass-mid and midrange-tweeter crossover (although the JLI61A has a bit of a bump). So you could use these mics for such purposes even without calibration.
- The WM61A lot 4A14 microphones are brilliant. The great news is that we have lots of these available for constructors!

Circuit description

The electronics to drive the microphone capsule is not complex, as shown in Fig.4.

The circuit has three main parts: buffers for driving the balanced output lines, a gain stage which includes some cunning frequency compensation and a power supply for the gain stage.

The first thing to keep in mind when looking at this circuit is that pins 2 & 3 of CON1, the XLR socket, act as both 48V DC power inputs and AC signal outputs. The 48V DC is 'phantom power' from the upstream equipment like a mixer or microphone preamplifier. It is dropped across the 6.8kΩ resistors in the phantom power source, allowing the Microphone to vary the voltages on these pins to feed the signals back.

PNP transistors Q1 and Q2 are emitter-follower buffers with 6.8V zener diode clamps between their collectors and emitters.

The DC bias point for Q1 and Q2 is established by the 150kΩ resistors between their bases and collectors. The current flowing from their emitters to their collectors provide the supply current to the rest of the circuit via R12.

Once power is applied, as the collector voltages of Q1 and Q2 increase, the base current through the 150kΩ resistors falls until DC equilibrium is established. For AC signals, Q1 and Q2 act as emitter-followers with the AC signals being coupled to their bases through 1µF electrolytic capacitors.

Is this really balanced audio? By driving the hot pin with the microphone output and the cold pin from ground, we provide a differential output from the Microphone. The balanced line receiver for the Microphone will subtract any signal on the cold line from the hot, providing the immunity from noise pickup in the cable we seek.

The 48V DC phantom supply is dropped across the 6.8kΩ series resistors in the microphone preamplifier and 5.6kΩ resistor R12 to the 6.8V limit set by zener diode ZD2.

The collectors of Q1 & Q2 will sit at around 32V, as exlained below. This voltage (and the current that establishes it) supplies power to the amplifying NPN transistor, Q3, and the ECM itself, in both cases via 5.6kΩ resistor R12.

The circuit includes 1nF and 2.2nF capacitors from pins 2 & 3 of CON1 to ground, with 47Ω resistors between them, to increase the immunity of the circuit to radio-frequency interference (RFI). These parts do little to affect the low-frequency audio signals or phantom power but will heavily attenuate ultrasonic signals.

Additionally, 470pF 'Miller' capacitors across the base resistors of Q1 & Q2 roll off the frequency response of these buffer transistors above audible frequencies.

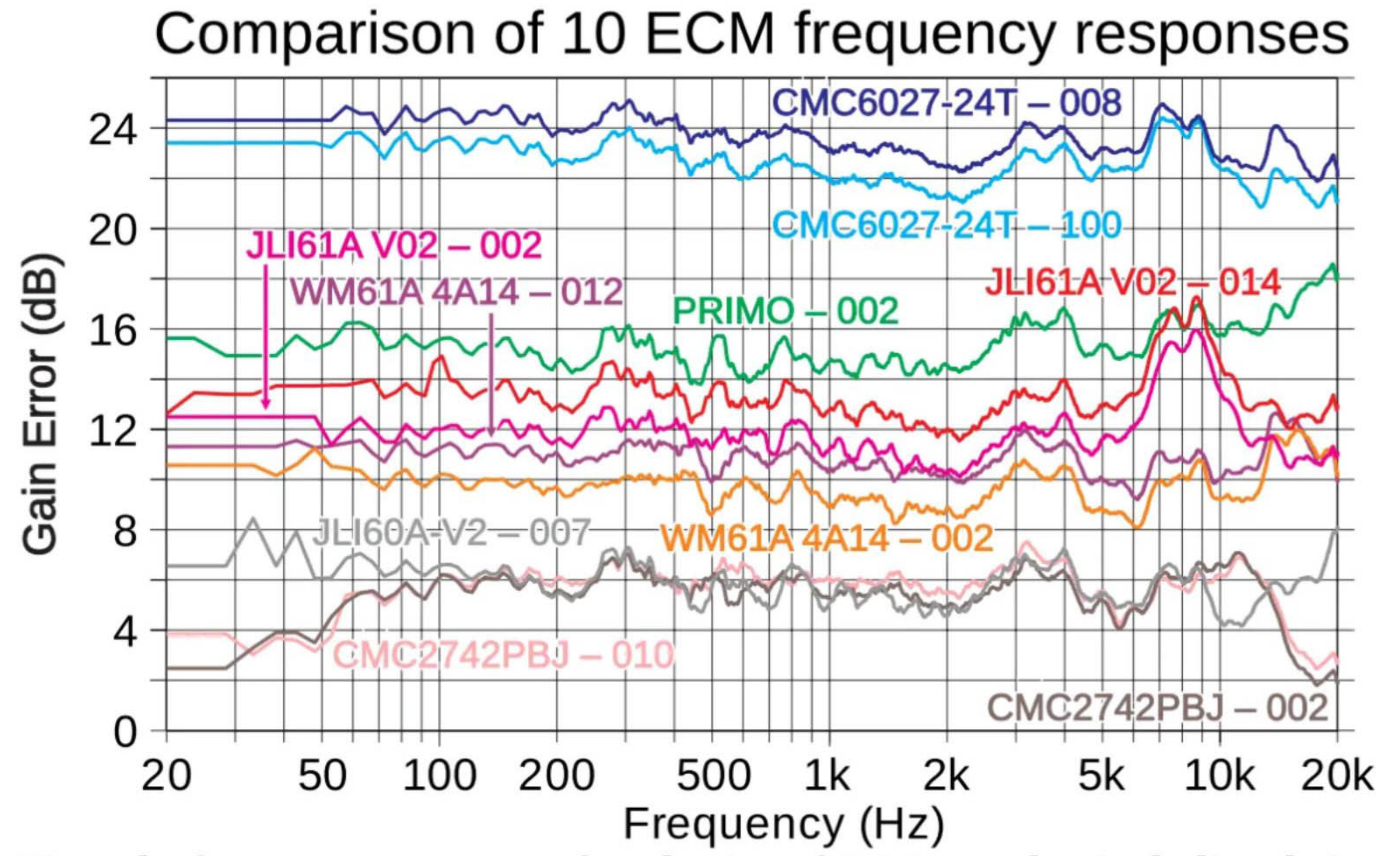


Fig.3: the frequency responses of a selection of ECM capsules, including their recommended frequency correction parts, but without calibration corrections. These curves themselves form the calibration correction files. The vertical offsets represent differences in sensitivity, but we are mainly interested in the flatness of each curve (flatter is better from a measurement perspective).

Power supply

The power supply for the ECM is very simple but includes plenty of filtering to get a stable DC supply from the hot and cold lines carrying our audio signal. We mentioned the 6.8V derived from the phantom power across ZD2. This is low-pass filtered to remove noise by the 100µF capacitor across ZD2, in combination with the source resistances (6.8kΩ & 5.6kΩ).

It is further filtered by another low-pass filter (330Ω/10µF) before being applied to Q3 and the ECM. This is because the signal from the ECM is so low in amplitude that any noise getting through could seriously degrade our signal-to-noise ratio (SNR).

Frequency compensation

Finally, we have the ECM interface and frequency compensation. This part of the circuit can be as simple as a bias resistor (R8 or R14) and an amplifying transistor (Q3).

During our tests, we found several microphones that required either boosting their output at high frequencies, attenuating at high frequencies, or a little of both to give a flat response.

Therefore, all our compensation is targeted at higher frequencies. Boost is achieved by R10/C12. These parts are in parallel with the emitter resistor of Q3 and thus increase the gain of Q3 at higher frequencies. We can set the corner frequency and the ultimate boost level by choosing the values of these parts.

Table 1 – Tested Microphone Capsules

Model	Source	Notes
Panasonic WM-61A	– AliExpress 1005004118951415	Gives the flattest response overall.
Panasonic WM-61A	– eBay 164187904055 – Silicon Chip SC6761	"Lot 4A14" – large quantity available; also gives a very flat response.
JLI-61A	– www.micbooster.com – www.jlielectronics.com – Silicon Chip SC6762	"Lot 3" – needs compensation for good performance.
JLI-61AY-102	– www.micbooster.com – www.jlielectronics.com – Silicon Chip SC6763	Better than the JLI-61A but still needs compensation.
CUI CMC-6027-24	– Mouser – Silicon Chip SC6764	Can have suffixes "T" or "L100" (they give the same performance). They are the most sensitive of the tested types and among the flattest response with compensation applied.
CUI CMC-2742PBJ-A	– Mouser – Silicon Chip SC6765	Requires compensation and calibration, giving a reasonably flat response but with roll-off below 50Hz & above 15kHz.
Kingstate KECG2740PBJ	– element14	Requires compensation for good performance.
Kingstate KECG2742TBL-A	– element14	Requires compensation for good performance.
Primo EM258	– www.micbooster.com	Excellent performer; expensive, no compensation required.

High-frequency attenuation is achieved by R13/C14, which are effectively in parallel with Q3's 2.2kΩ collector resistor. Again, these parts can set the corner frequency and ultimate attenuation.

This modification of the simple transistor amplifier (Q3) provides a powerful tool to tailor the response of a capsule. By implementing these corrections inside the Microphone, we achieve a respectably flat frequency response and leave only 'fine-tuning' to a calibration file.

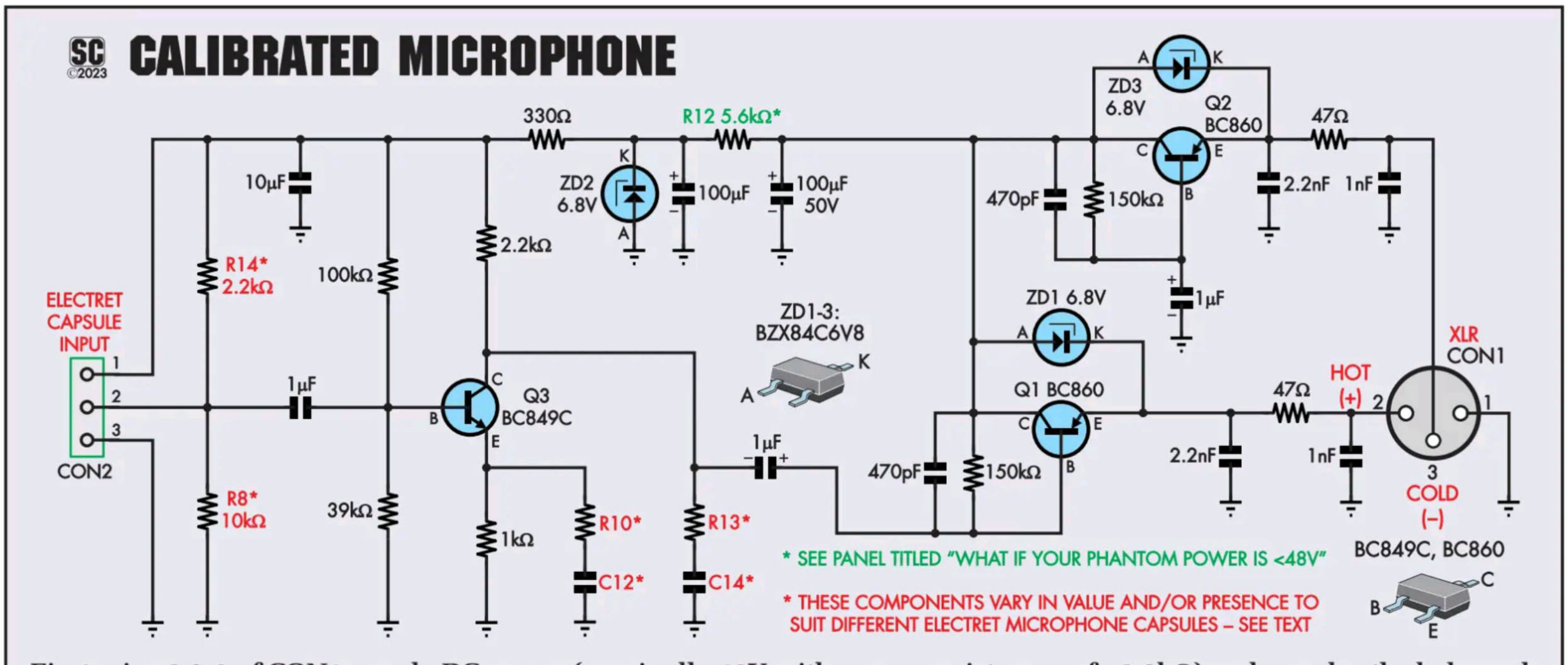

SC ©2023
CALIBRATED MICROPHONE
ELECTRET CAPSULE INPUT
CON2
1
2
3
R14* 2.2kΩ
R8* 10kΩ
10µF
100kΩ
39kΩ
1µF
330Ω
2.2kΩ
Q3 BC849C
B
C
E
1kΩ
R10*
C12*
R13*
C14*
ZD2 6.8V
K
A
R12 5.6kΩ*
100µF
100µF 50V
ZD1-3: BZX84C6V8
A
K
1µF
470pF
150kΩ
ZD3 6.8V
Q2 BC860
ZD1 6.8V
Q1 BC860
1µF
47Ω
2.2nF
1nF
HOT (+)
XLR CON1
COLD (–)
BC849C, BC860
B
C
E
* SEE PANEL TITLED "WHAT IF YOUR PHANTOM POWER IS <48V"
* THESE COMPONENTS VARY IN VALUE AND/OR PRESENCE TO SUIT DIFFERENT ELECTRET MICROPHONE CAPSULES – SEE TEXT

Fig.4: pins 2 & 3 of CON1 supply DC power (nominally 48V with source resistances of ~6.8kΩ) and are also the balanced audio signal outputs. PNP transistors Q1 & Q2 drive the audio signals onto those pins; their collector-emitter currents (and any current shunted by parallel zener diodes ZD1 & ZD3) also provide a power supply for amplifier transistor Q3 and the electric mic. The transistors shown are for the SMD version. Note that R8 is only fitted with 3-wire ECMs.

Fig.5 shows how the compensation works. The green trace is the frequency response of the circuit using a JLI61A ECM with no compensation; note the ~7dB peak at about 7.5kHz. The red curve shows the compensation achieved with R10 = 220Ω, C12 = 12nF, R13 = 2.2kΩ & C14 = 15nF, and the blue curve is the much-flatter ultimate frequency response achieved.

There is still a small peak of about +3dB, but we can't knock it down further without overly attenuating signals at about 2-6kHz and 10-20kHz. It isn't much bigger than some other peaks after compensation, anyway.

Most ECM capsules within a batch behave similarly. During our calibration process, we set aside any parts that were outliers. Thus, you are guaranteed to get a pretty good response without the compensation file, and a very flat response with it.

If you source your own ECM capsules, you will need to optimise the response and generate a calibration file. This project provides everything you need to do that, except a calibrated microphone against which to make the required measurements.

Two PCB options

If possible, we recommend you build the SMD version where all parts are on the top side. However, we have also laid out a through-hole version and managed to squeeze it into a 13mm wide PCB, but it is 99mm long rather than the 64mm of the SMD version. The two versions are shown in Figs.6 and 7.

Why bother with analog frequency compensation?

If we are supplying a calibration file, why not just leave all the corrections to that file, and omit R10/C12 and R13/C14 from the circuit?

If the microphone would only be used in a measurement system with a calibration file installed, there would be no reason to care that the Microphone itself had significant errors in its inherent frequency response.

However, we wanted to make a microphone that, in itself, was quite respectable, leaving calibration via the associated file for fine-tuning. That means you could use it with other software without calibration support and still get reasonable performance.

We also wanted to make a microphone that could be used for recording, with the possibility of tailoring it for vocal and instrumental use. By including these parts, we can do both.

Because our calibration files are generated with the specified frequency compensation parts installed, if you use one of our ECM capsules and calibration file, you must load the recommended parts to get optimal performance.

Both these boards have been made thin enough to fit in a 'skinny' microphone case. Neither is hard to assemble, but we reckon the SMD one is less fiddly than the through-hole version due to all the parts mounting on one side.

The smallest parts on the SMD board are the SOT-23 transistors and zener diodes, which are not that hard to solder. We hand-built about 20 prototypes and, without a doubt, soldering the ECM capsule pins is fiddlier than anything on the SMD PCB. So, unless you have plenty of room to house the through-hole PCB, we recommend you make the effort to build the surface mount version.

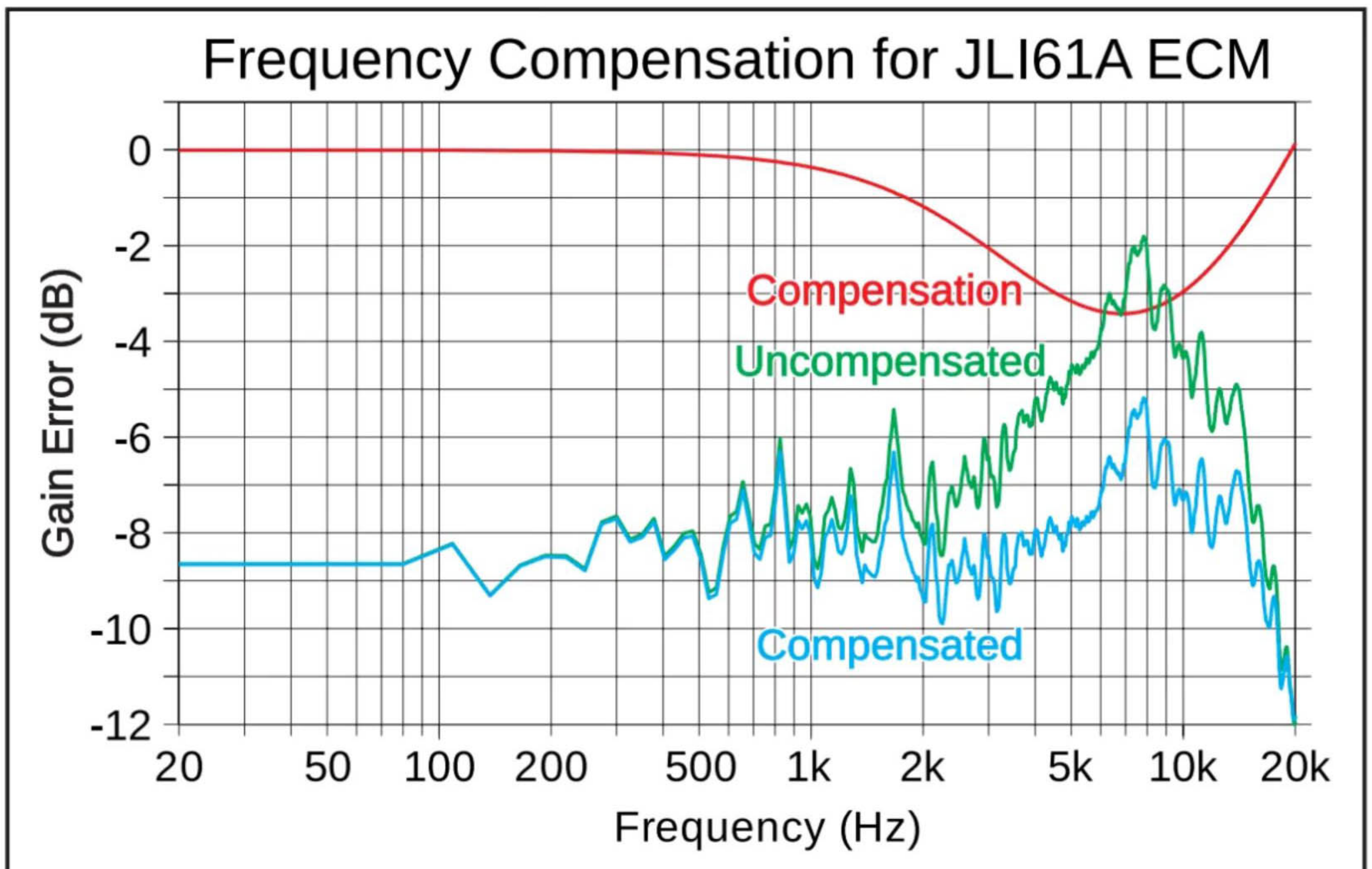


Fig.5: the frequency compensation for a JLI61A microphone. Here we have set the compensation (red curve) to push down the peak in its response (green curve) while limiting attenuation at high frequencies. This is not perfect, as we need to match a batch of microphone elements with these parts, but we reckon ±2dB across most of the band is a good result for a microphone.

SMD board assembly

The SMD version of the board is coded 01108231 and measures 64 × 13mm.

Start by fitting the resistors and ceramic 'chip' capacitors. There are variations depending on whether you have a 2-pin or 3-pin ECM and what compensation components are required. If you have a 2-pin ECM, fit R14 (2.2kΩ, near CON2) and leave off R8 (10kΩ). If you have a 3-pin ECM, fit R8 (10kΩ) and leave off R14 (2.2kΩ, near CON2).

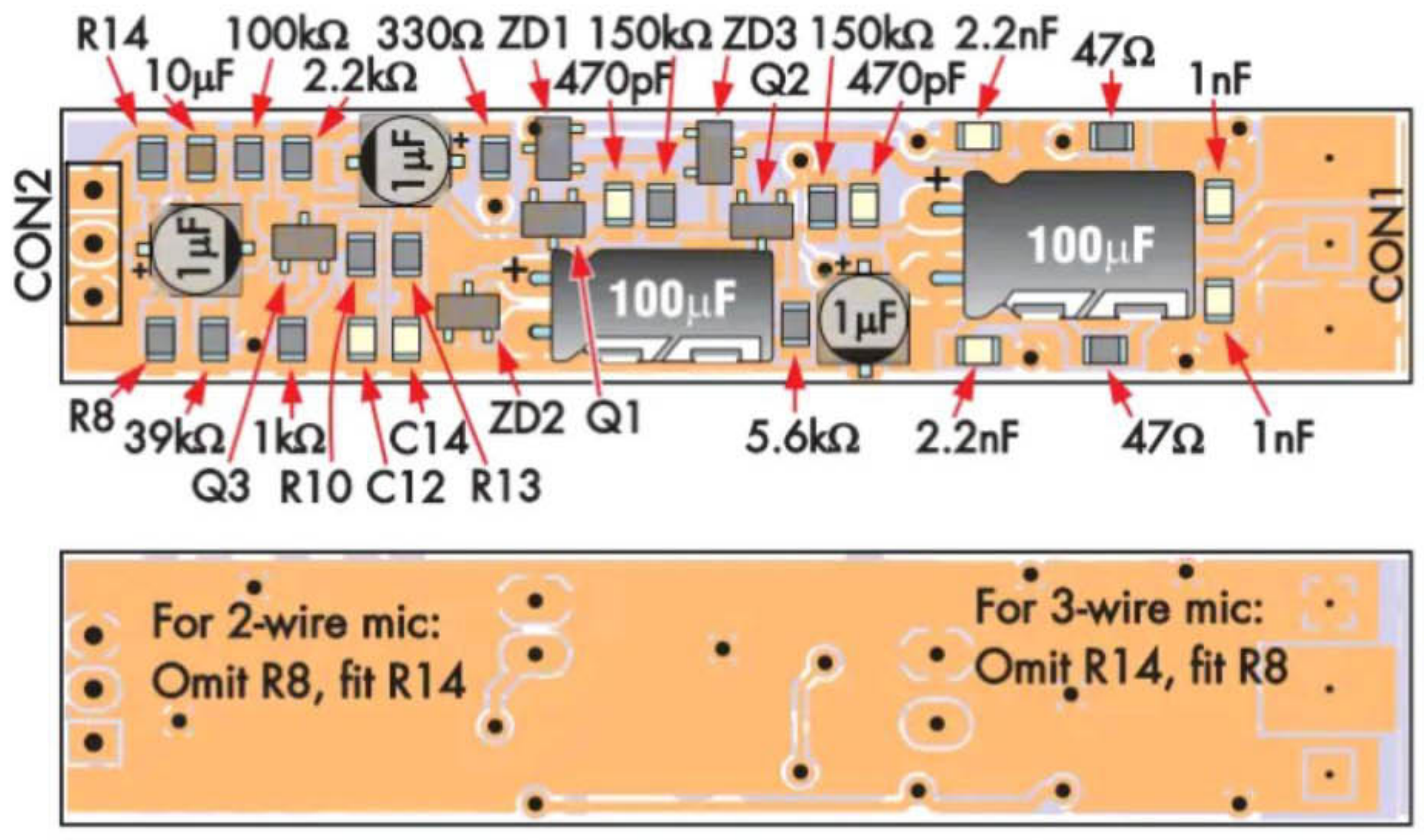
The compensation components are R10, R13, C12 and C14; they are all between Q3 and ZD2. Refer to Table 2 to determine which of these you need to fit for your ECM (if you purchased it from our shop, it will come with these components).

Next, mount the three transistors (one NPN, two PNP) and three zener diodes. Watch out as these are all in SOT-23 cases. If you get them mixed up, you will find a code engraved on the top of the devices that identifies each.

Unfortunately, this can vary depending on the manufacturer, so you might need to check the data sheet. Still, they will probably be one of these (a question mark '?' represents any letter or number):

BC849C: 2C?, 49C or 8DC
BC860: 9EA/B/C, 4F? or 4G?
BZX84C6V8: Z5, ?61, D4P, WC or KB

Failing this, you can use a DMM on diode test mode or our SMD Test Tweezers (from the February 2022 & 2023 issues) to find the base/emitter pins


R14
10µF
100kΩ
2.2kΩ
330Ω
ZD1
470pF
150kΩ
ZD3
Q2
150kΩ
470pF
2.2nF
47Ω
1nF
CON2
1µF
1µF
100µF
100µF
1µF
CON1
R8
39kΩ
1kΩ
C14
ZD2
Q1
Q3
R10
C12
R13
5.6kΩ
2.2nF
47Ω
1nF
For 2-wire mic:
Omit R8, fit R14
For 3-wire mic:
Omit R14, fit R8

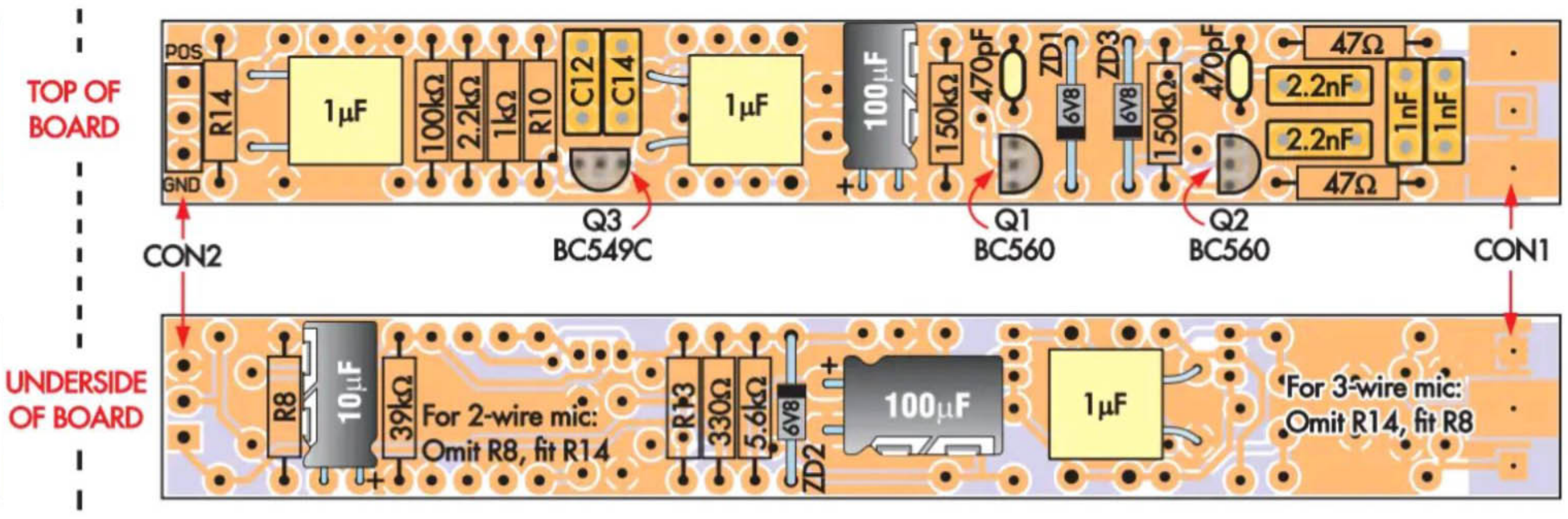

TOP OF BOARD
UNDERSIDE OF BOARD
POS
GND
R14
1µF
100kΩ
2.2kΩ
1kΩ
R10
C12
C14
1µF
100µF
150kΩ
470pF
ZD1
6V8
ZD3
6V8
150kΩ
470pF
47Ω
2.2nF
2.2nF
47Ω
1nF
1nF
CON2
Q3
BC549C
Q1
BC560
Q2
BC560
CON1
R8
10µF
39kΩ
For 2-wire mic:
Omit R8, fit R14
R13
330Ω
5.6kΩ
6V8
ZD2
100µF
1µF
For 3-wire mic:
Omit R14, fit R8

Fig.6 (left): this is the SMD version of the PCB. Note that the values (and presence) of R10, R13, C12 and C14 are varied to match your ECM capsule. Either R8 (10kΩ) or R14 (2.2kΩ) is fitted depending on whether you have modified your capsule; for an unmodified (2-pin) capsule, leave off R8 but fit R14.

Fig.7 (right): to avoid making it too much bigger than the SMD version, the through-hole (TH) PCB has parts mounted on both sides. In most cases, the solder joints are still accessible should you need to make changes or repairs. It is the same width as the SMD version but about 50% longer, meaning it won't fit in the inexpensive plastic case described in the article.

of the devices. With the single pin at the top, the base will be at lower left and the emitter at lower right.

If you get a ~0.65V reading with the red probe on the left, it's an NPN transistor (BC849), or on the right, it's a PNP transistor (BC860). If you get neither, it's likely a zener diode. They will give a similar reading with the red probe on the lower left pin and the black probe on the top pin (that forward-biases the zener diode).

The three remaining SMDs are the three non-polarised 1µF electrolytic capacitors. These come in metal cans mounted on plastic bases. Like polarised electros, the bases have chamfered edges on two corners that normally indicate the positive end. Because they are not polarised here, it doesn't matter which way around you mount them.

Since two of these capacitors could be polarised types, we've left polarity markings on the PCB, but we've specified all three as NP caps to make things a bit easier.

In terms of components on the board, that just leaves the two through-hole capacitors, which are both 100µF parts but with different voltage ratings. Solder them laid over on their sides, as shown in our photos, so that the assembly will fit in a small-diameter tube. The striped negative end must go towards the bottom of the PCB, with the longer positive leads to the pads marked with + symbols.

Through-hole assembly

The through-hole version of the board is coded 01108232 and measures 99 × 13mm. This can be assembled as usual, but it's easier to fit all the components on one side (ideally the top side) before starting on the other.

Fit the axial parts first (resistors and zener diodes, watching the zener diode's cathode stripe orientation), then the MKT and ceramic capacitors with some laid over, as shown in Fig.7. Leave the electrolytic capacitor off initially to provide better access to the remaining solder joints.

Refer to the section above regarding which of the optional resistors and capacitors to install (R10, R14, C12 & C14).

Next, fit the transistors as shown, pushing them fully down before soldering and trimming their leads, then flip the board over and solder the axial components (resistors & zener diode) on that side. Again, see the section above for what to do about R8 and R13. Follow with the single 1µF MKT on this side of the board, laid over, then the two electros, laid over and orientated as shown.

Note that the 100µF 50V electrolytic capacitor is specified in the parts list as having a maximum diameter of 8mm. A 47µF 50V electrolytic capacitor is also fine to use, as long as its 8mm in diameter.

Finally, flip the board back over and fit the last electrolytic capacitor (100µF) on that side.

Capacitor selection

Like the other low-value capacitors

Table 2 – microphone capsule calibration component values

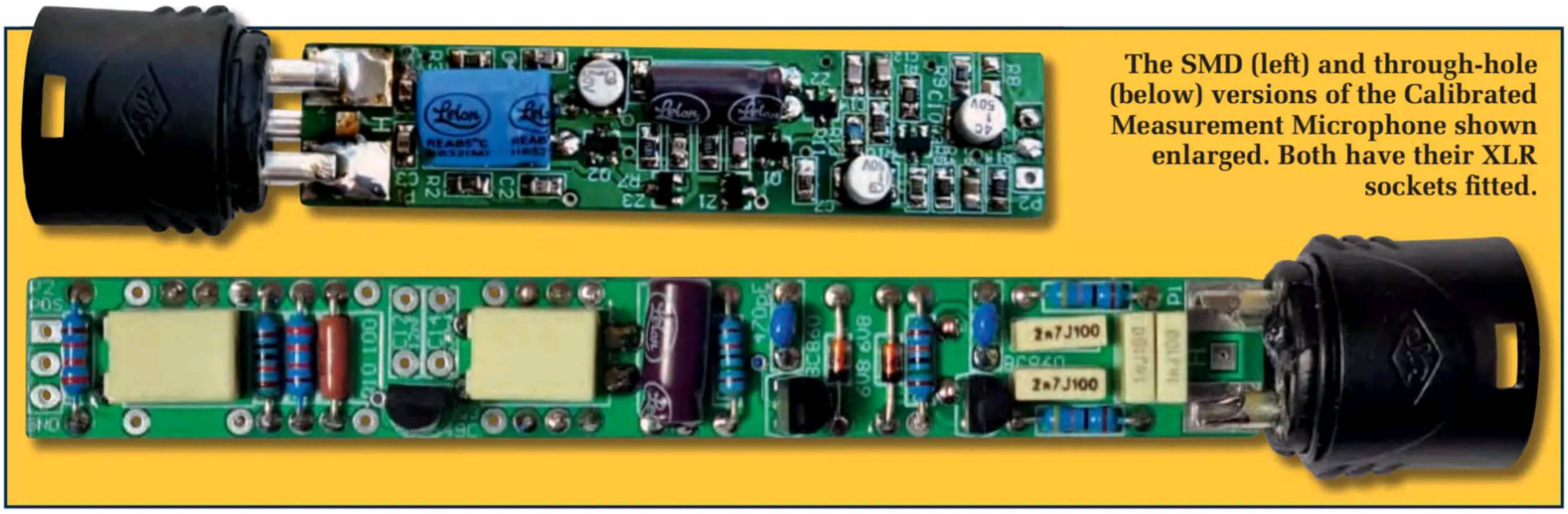
Manufacturer	Part	R10	C12	R13	C14
Panasonic	WM61A (AE)	N/A	N/A	100Ω	5.6nF
Panasonic	WM61A lot 4A14	N/A	N/A	100Ω	6.8nF
JLI	JL61A	220Ω	12nF	2.2kΩ	15nF
JLI	JL60A-V02	220Ω	12nF	10kΩ	6.8nF
CUI Devices	CMC-6027-24T	220Ω	18nF	3.9kΩ	18nF
CUI Devices	CMC-6027-24L100	220Ω	18nF	3.9kΩ	18nF
CUI Devices	CMC2742PBJ	820Ω	4.7nF	2.2kΩ	8.2nF
Kingstate	KECG2740PBJ	10Ω	12nF	3.9kΩ	6.8nF
Kingstate	KECG2742TBL-A	100Ω	8.2nF	3.9kΩ	6.8nF
Primo	EM258	N/A	N/A	N/A	N/A

What if your phantom power is <48V?

Phantom power for microphones is an old standard. Like many standards, it is not particularly well followed.

Most phantom power systems operate at 48V. For 48V, your preamplifier/mixer will have 6.8kΩ series resistors from the 48V supply. However, if it has a 24V supply instead, they will be 1.2kΩ, or 680Ω for a 12V supply.

R12 should be 5.6kΩ to suit 48V systems or 1.5kΩ for systems delivering 24V DC bias or less. Our calculations show that the Mic will work with 12V & 24V DC supply systems with R12 set to 1.5kΩ.



The SMD (left) and through-hole (below) versions of the Calibrated Measurement Microphone shown enlarged. Both have their XLR sockets fitted.

(<1µF), the compensation capacitors, which range from 4.7nF to 18nF (if present) must be plastic film (eg, MKT) types for the through-hole board or NP0/C0G ceramics for the SMD board. Don't be tempted to use cheaper X5R, X7R or Y5V ceramic capacitors. They have a high voltage coefficient and thus are highly non-linear; definitely not what we want as part of a filter network!

The microphone housing

Regardless of which PCB you've assembled, the remainder of construction proceeds in much the same manner.

The connection to the XLR socket will depend a lot on the approach you have to construction. In many cases, you can push the PCB between the XLR pins and simply solder the PCB to the pins directly. How this fits depends on your chosen connector and how you house the PCB. If you are using a metal housing, add a wire link from the PCB ground pin on the XLR to the housing.

We want the ECM insert in 'free space' and with minimal reflections to get flat performance. All the ECM inserts we recommend are 6mm in diameter.

We will present two ways to achieve the required mounting, one based on metal pipe hardware and the other using plastic pen cases.

Photo 1 (below) shows the collection of metal parts we used to build our Microphone, while Photo 3 (overleaf) shows the parts to make the plastic version. How you go about this comes down to what you can find in your shed and parts drawer. The three key goals are:

- We want the ECM insert mounted at the end of a 100-150mm tube that it just fits inside.
- We want a section that can house the PCB. Both PCBs are just under 13mm wide, but the electros are quite thick, so a tube with an inner diameter of 18-20mm is ideal.
- We want an XLR connector at the other end.

If you have a vocal or musical instrument application, you might take an alternative approach to the housing.

Copper housing

We used a K&S #9825 brass tube for the ECM, which is 7mm outer diameter with 0.45mm wall thickness. An alternative is K&S #8132 brass tube, which is 9/32 inches (7.14mm) in diameter with 0.014-inch (0.36mm) wall thickness. These are available from hobby shops in 305mm lengths for about £4, enough to make two or three microphones.

The challenge is to expand from the 7mm tube to the 20mm or ¾-inch (19mm) tube that houses the PCB and XLR connector. You will likely find your own approach by looking through your parts bin.

We adapted between the two different diameter pipes by first using the backshell from an Altronics P0192 RCA socket, which the brass tube just squeezes into, then fitting this to the small end of a 15mm to 20mm copper capillary adaptor. This might sound complicated, but it is not hard; Fig.9 and the photos show how it came together.

The SMD version of the PCB fits into the 20mm tube easily; the through-hole version is no wider, but it is quite a bit longer.

In more detail, the 7mm tube was a tight push-fit into the RCA backshell. We then wrapped the backshell in 1mm bare copper wire, making it a tight fit into the 15mm to 20mm reducer. Because these parts are all copper and brass, we simply soldered them together.

There are many ways to do this, but after some thought, we assembled the parts using liberal amounts of solder paste (see Photo 2) and baked it in our reflow oven at 230°C for a few minutes. You could use any oven you don't cook food in.

We also successfully made microphones using a butane torch to heat the parts and literally soldered them using regular solder wire.

We won't present exact instructions here, as your parts will likely vary. Some ingenuity and finding surplus or recycled parts from your shed will save you a lot of money and hopefully be a fun challenge. The key parameter is that you adapt the XLR section to the 7mm tube 100-150mm long.

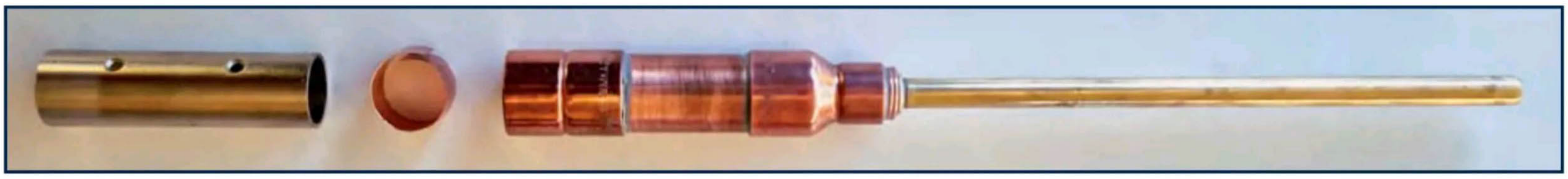


Photo 1: we made our 'high-end' microphone housing from a 150mm length of 7mm brass tubing with a collection of copper pipe fittings, ¾-inch (19mm) copper pipe and an XLR male-to-male adaptor.

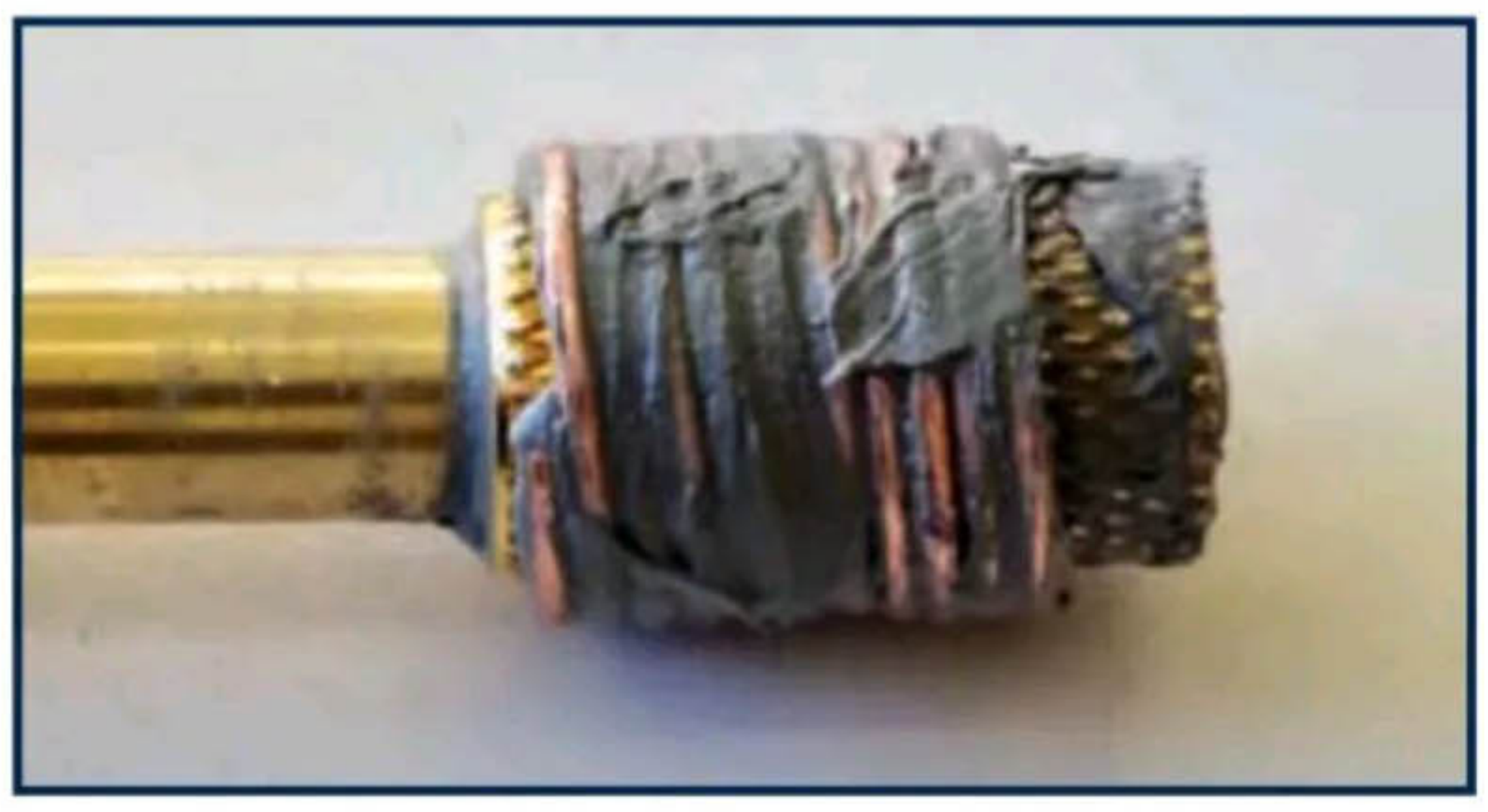


Photo 2: we pushed the 7mm tube through the RCA backshell, which was a tight fit. We then wrapped 1mm copper wire around this, which makes this a close fit to the 20mm to 15mm capillary reducer. The grey substance is solder paste.

The assembly process was to pull the microphone wiring through the 7mm tube, with the ground and output wires soldered to the ECM capsule (see Fig.8). We felt confident nothing would short, so we simply tacked the tips of the hookup wire to the pads/pins on the ECM capsule.

At the plug end, we snipped the microphone wires off about 30mm past the opening and connected them to the PCB. The green (ground) wire goes to the ground pin, and the black wire (microphone output) to the middle pin.

We then wrangled the wires into the microphone housing, and once everything was lined up, we fixed the plug to the housing.

If you are using the Altronics XLR male-male adaptor, it is a simple matter of pushing the board in until the screw

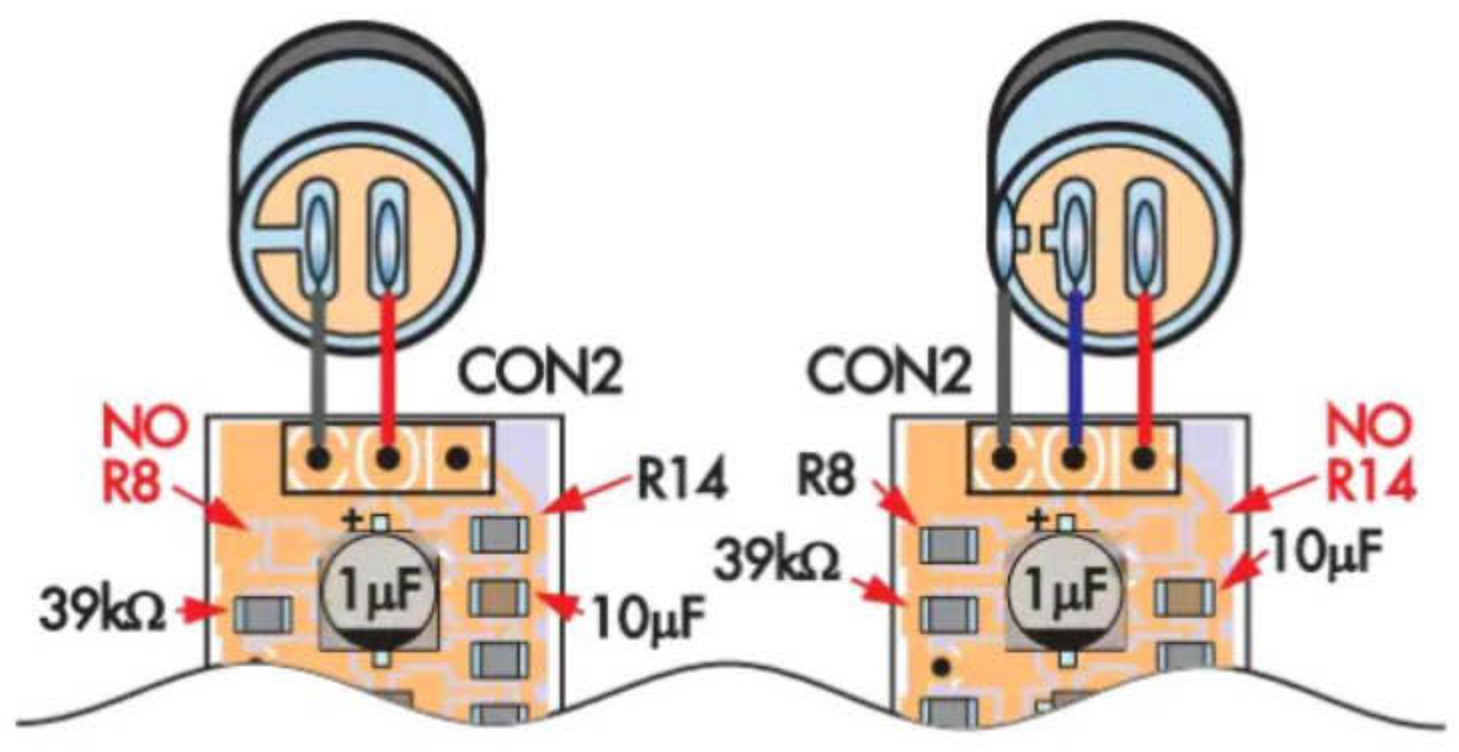


Fig.8: how to wire up a regular two-wire ECM (left) and modified 'Linkwitz' three-wire ECM (right); note the differences in R8 & R14. The arrangement is the same for the through-hole board.

Tuning your microphone response

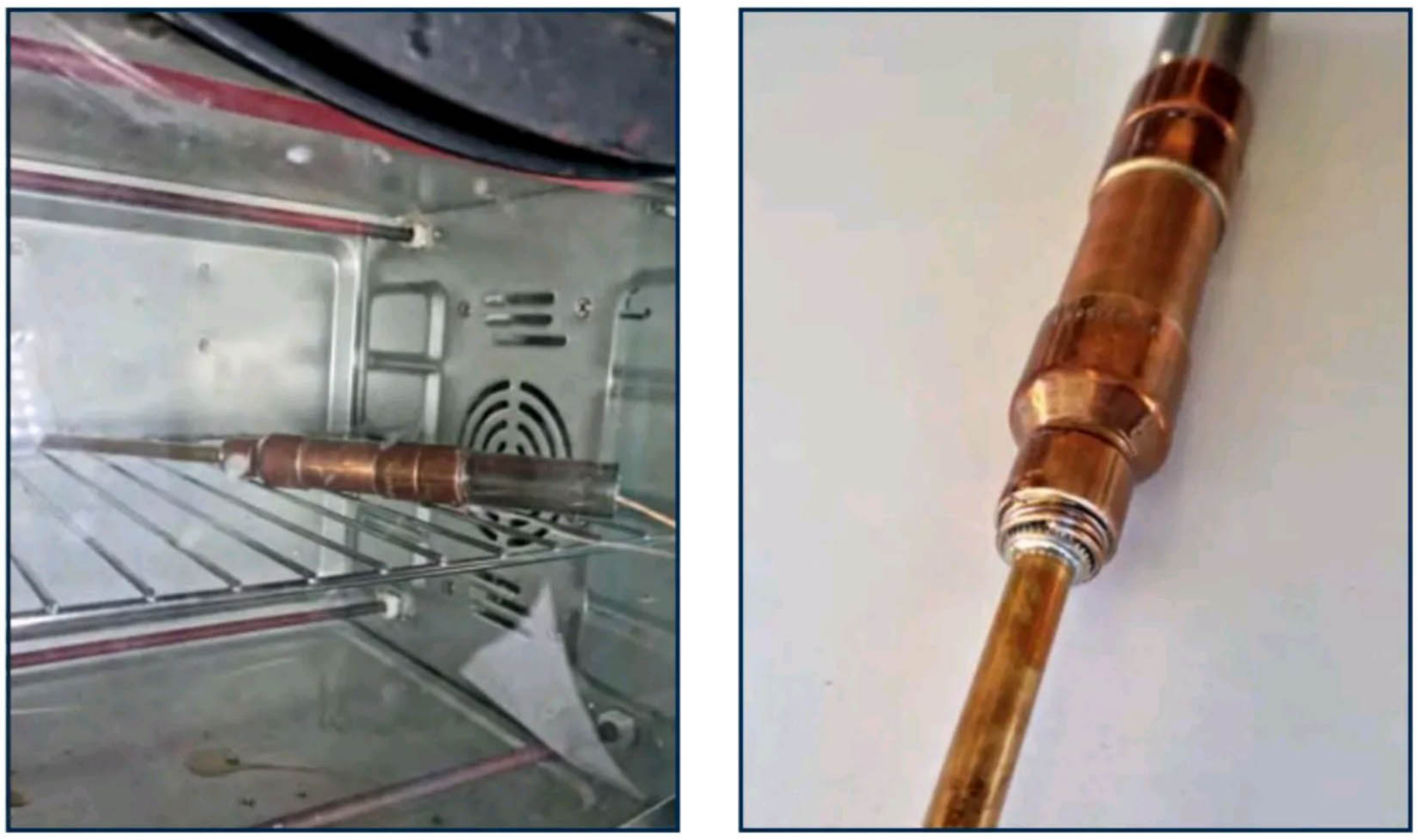
Our goal with a measurement microphone is a reasonably flat response before calibration and a flat response after calibration. If you purchase a calibrated ECM capsule from the Silicon Chip Online Shop, we will provide the necessary parts to load for response tuning. You will also get a calibration file, giving as close to a flat response as we can achieve with our equipment.

Alternatively, you may want to tailor the response of your Microphone. In that case, you can download an LTspice model from the Silicon Chip website (associated with this article). This can be used to model your response while varying the tuning components. The following is a general guide to tweaking the response:

- C12 and R10 provide control over high frequency gain, with C12 setting the corner frequency. C12 increases the gain with frequency by reducing the emitter resistance, which is initially 1kΩ. R10 allows the ultimate gain of this combination to be set. Conceptually, if R10 is set to 1kΩ, then, at very high frequencies, this results in two 1kΩ resistors in parallel for a final gain of two times or 6dB.
- R13 and C14 set the gain roll-off at high frequencies. While these go to ground, they are effectively in parallel with the 2.2kΩ collector resistance. This is reduced by R13, which directly reduces the gain of this stage. R13 sets the ultimate attenuation of this stage, and C14 the corner frequency.

You will also find the gain model in our “Analysis.odt” spreadsheet. While this is simpler to work with than LTspice, this spreadsheet is very much an engineering tool, so use it with caution. While the concept of how R10, R13, C12 and C14 interact is simple, getting the response you want can be tricky.

The values shown in Table 2 are what we found to be effective with batches of capsules we purchased. These will be a good starting point for you to experiment if you have the ability to check your calibration.



Reflowing the solder on the enclosure can be done with any regular oven by baking at 230°C. However, you shouldn’t use an oven that you cook food with. The final result is shown in the photo on the right.

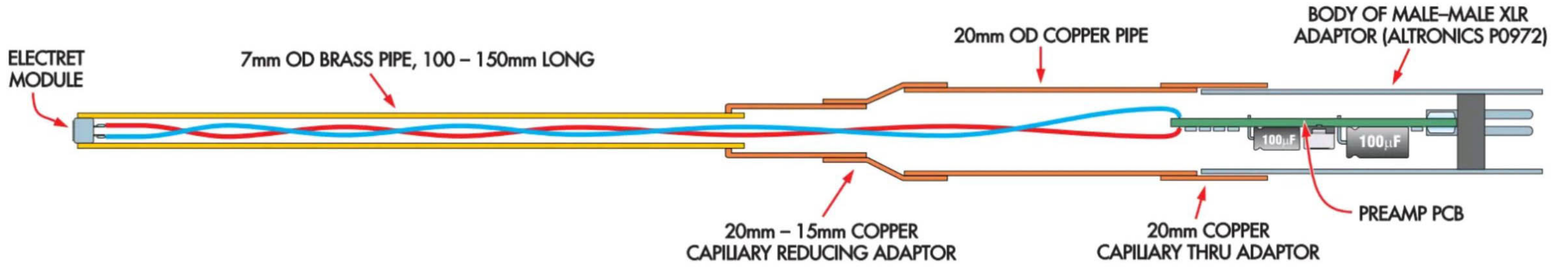

ELECTRET MODULE
7mm OD BRASS PIPE, 100 – 150mm LONG
20mm OD COPPER PIPE
BODY OF MALE–MALE XLR ADAPTOR (ALTRONICS P0972)
100µF
100µF
PREAMP PCB
20mm – 15mm COPPER CAPILLARY REDUCING ADAPTOR
20mm COPPER CAPILLARY THRU ADAPTOR

Fig.9: we used an Altronics XLR adaptor for the plug, which is a decent fit into a 20mm diameter copper pipe. We then used a capillary reducer and RCA socket shell to adapt that to the 7mm brass tube for the ECM. They came together very well with a few shims and some solder.

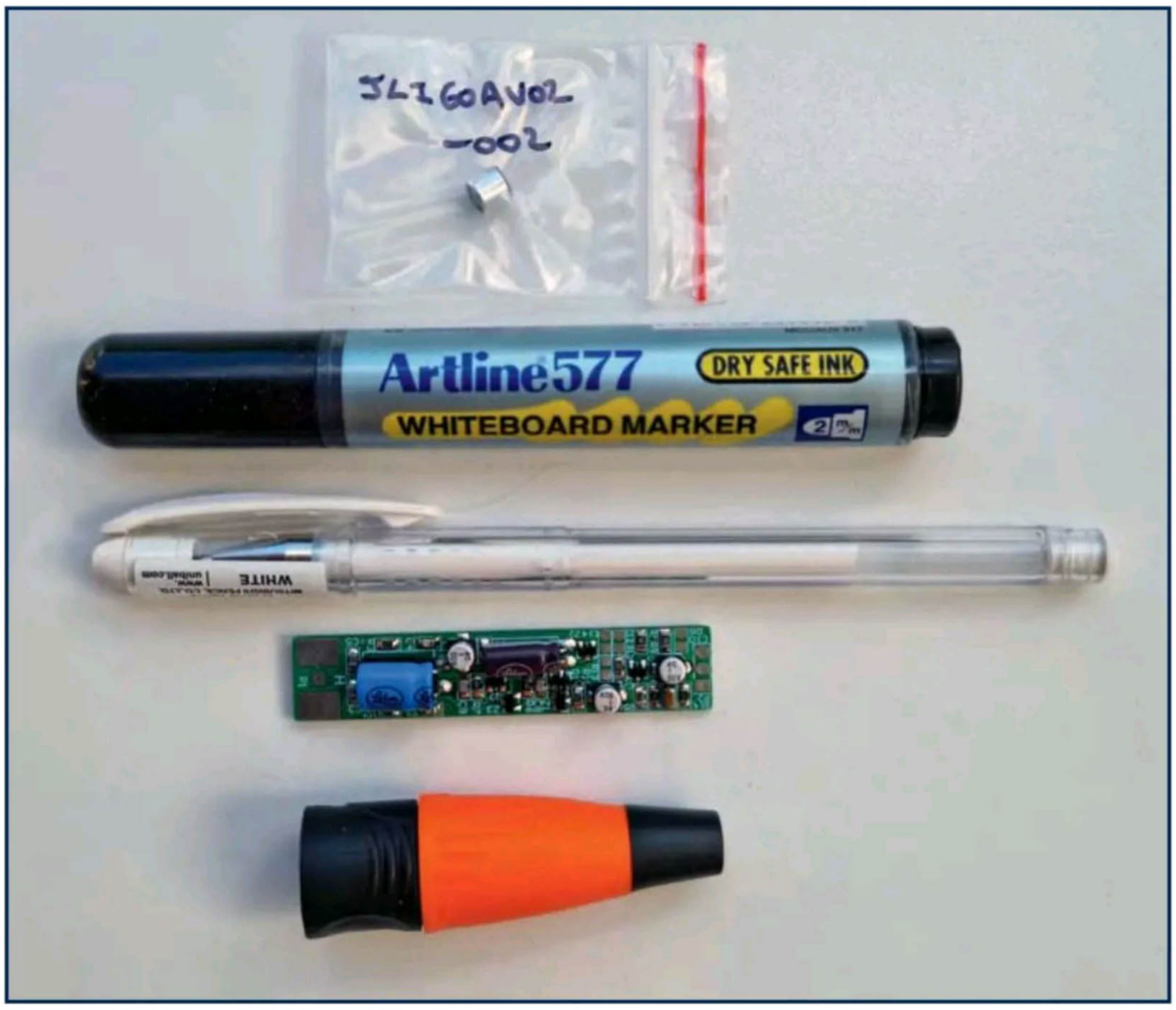
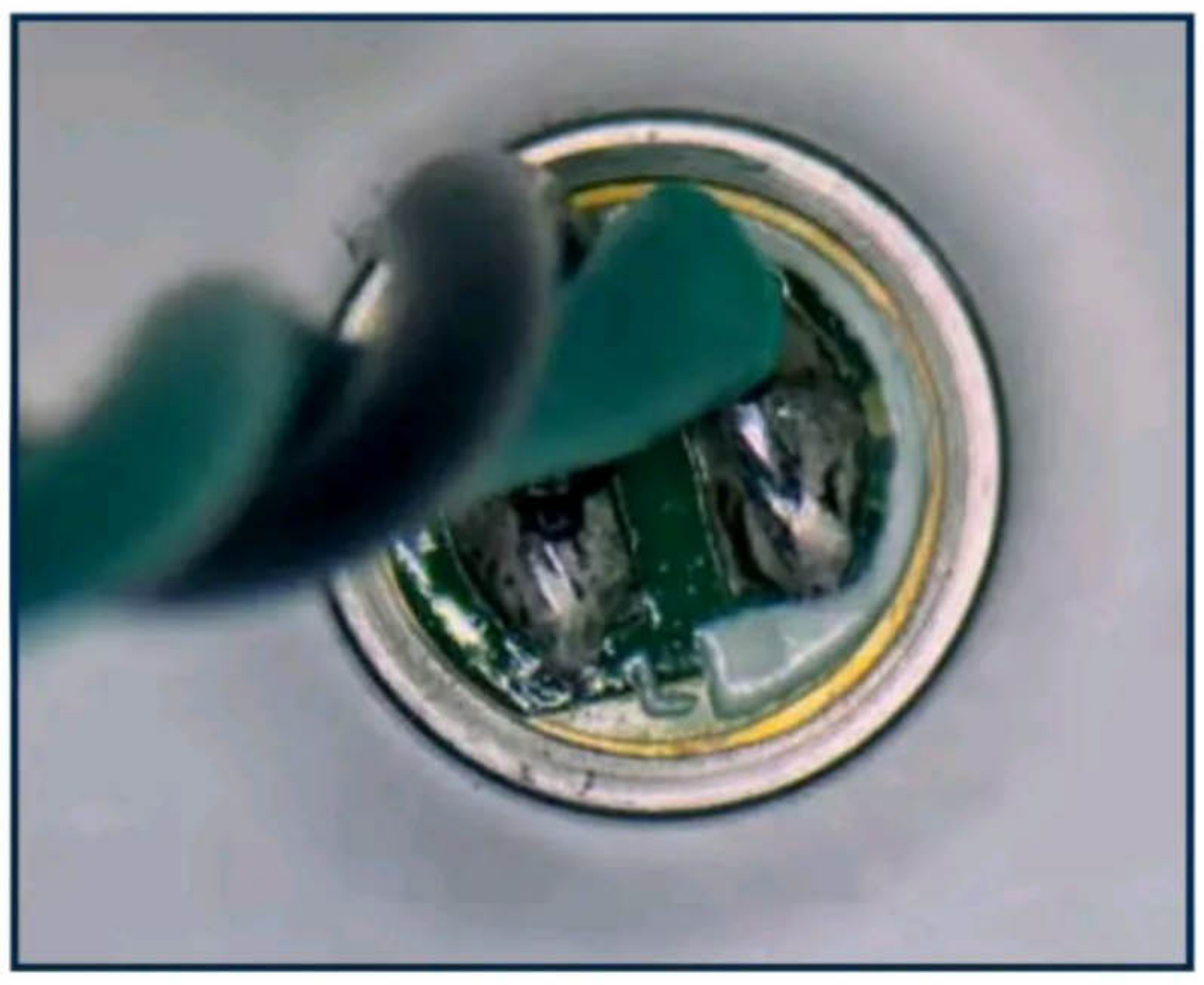


Photo 3: the very inexpensive microphone housing is made from a whiteboard marker and Biro pen case. An epoxy glue (Araldite) was used for the XLR housing joint.



A close-up of the interior wiring required for the microphone.

hole in the plug lines up and inserting the screw. You are then ready to go.

Plastic pen based housing

As mentioned at the start, a major driver of this design was to keep the cost low. Copper pipe is great if you have off-cuts in the shed, but buying it is pretty expensive. So we looked for a cheap and accessible way of mounting the 6mm capsule at the end of a thin tube, and something suitable for housing the electronics.

During one of the author's less lucid moments, likely due to ingesting an unhealthy amount of coffee, the seemingly silly idea of using a mix of plastic pens popped into his head. He found some cheap Biros at Officeworks and some whiteboard markers that, with a bit of drilling and gluing, made an inexpensive microphone housing.

If you use whiteboards (eg, at work), you will likely have a ready supply of dried-up markers. The SMD version of the board fits in these perfectly, although the through-hole version is too long. Even better, if you take an Altronics P0823 XLR plug and throw away all but the plug section, it fits perfectly into our whiteboard marker case, as shown in Photo 4.

The assembly process is similar to that for the copper tubes but quite a bit easier. First, strip the whiteboard marker apart and clean it out. Cut the tab off the XLR connector with side cutters to allow you to solder to the PCB. Cut the top of the whiteboard

How we generated calibration data for hundreds of ECMs

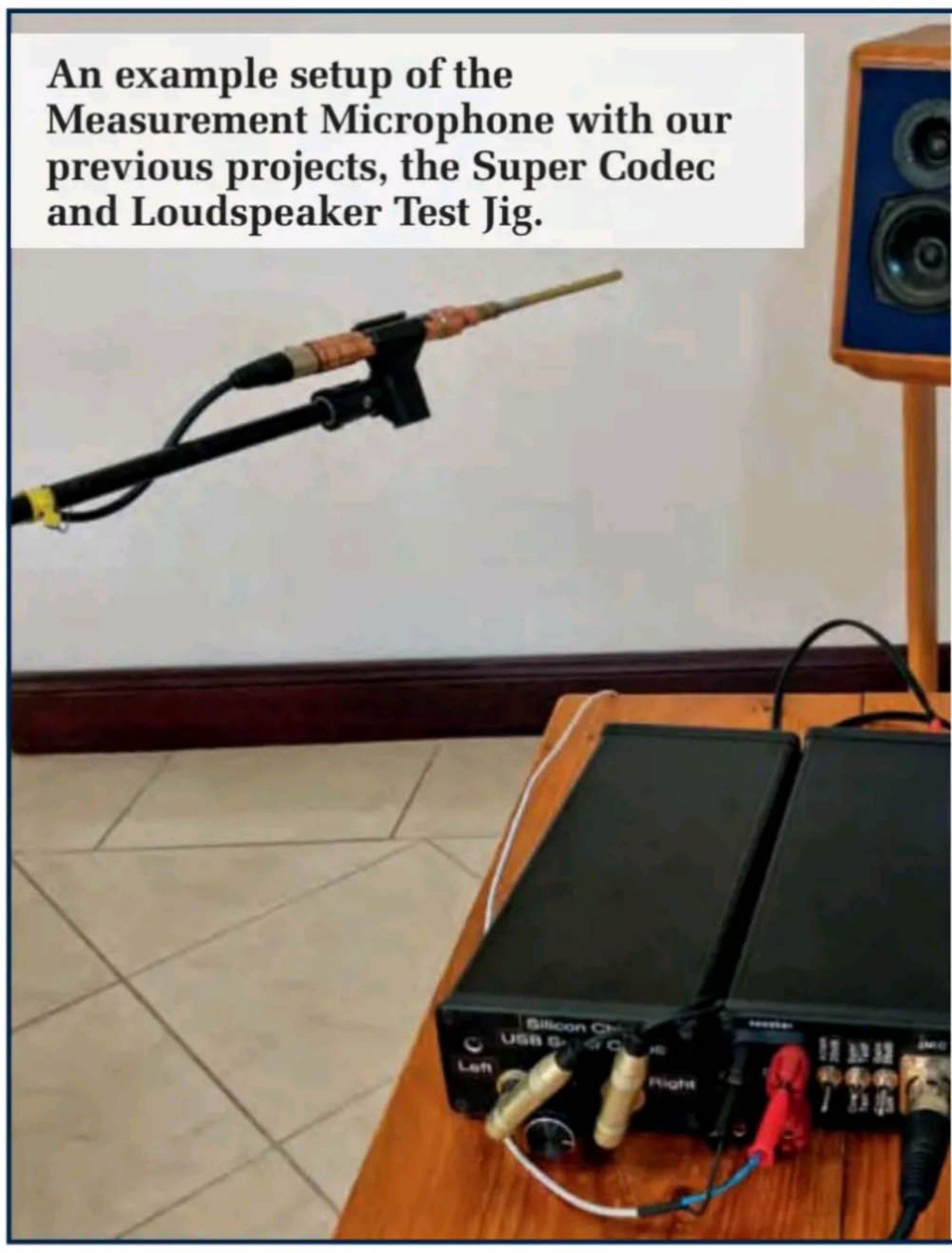
Our calibration process generates a calibration file for Speaker Workshop that allows us to measure the error of an ECM capsule from a flat response. To do this we:

- Measure the SPL of a speaker at an exact location relative to that speaker using our calibrated Dayton EMM-6 microphone (without its calibration coefficients).
- Subtract the calibration coefficients for our Dayton microphone from the measured values and export the result as a "CAL file".

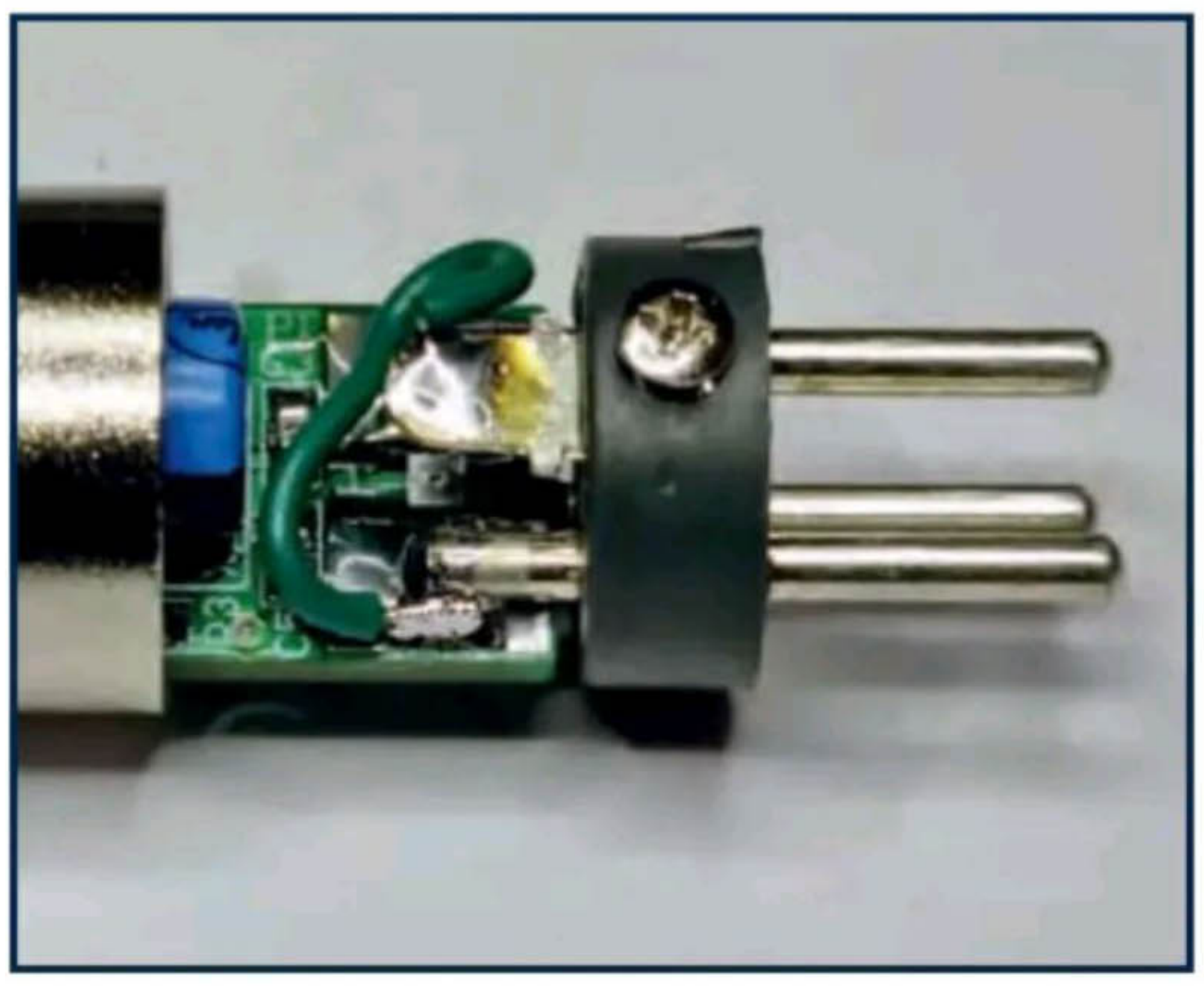
Using this as this synthetic calibration file, we will generate the calibration correction file for the connected microphone if we measure at the same location. We verified that this worked by running a measurement on the same Dayton EMM-6 microphone and confirmed that it produced the expected calibration values.

We can then substitute our ECM capsules, and providing we get them in the exact same spot, generate suitable calibration files for those capsules. By labelling each ECM with a number that matches the file saved, anyone who purchases that module can find and use the calibration data we generated.

We made a special spring-loaded jig that allows ECM capsules to be popped in and measured easily, speeding up this process. We also created a simple jig to ensure we always made the measurements at the exact same location relative to the speaker.



An example setup of the Measurement Microphone with our previous projects, the Super Codec and Loudspeaker Test Jig.



The XLR socket wiring on the SMD version of the Microphone.

marker off and drill the end so you have a tight fit for the Biro tube, then fix the Biro in place with super glue. See the first and last pages of this article for the final result.

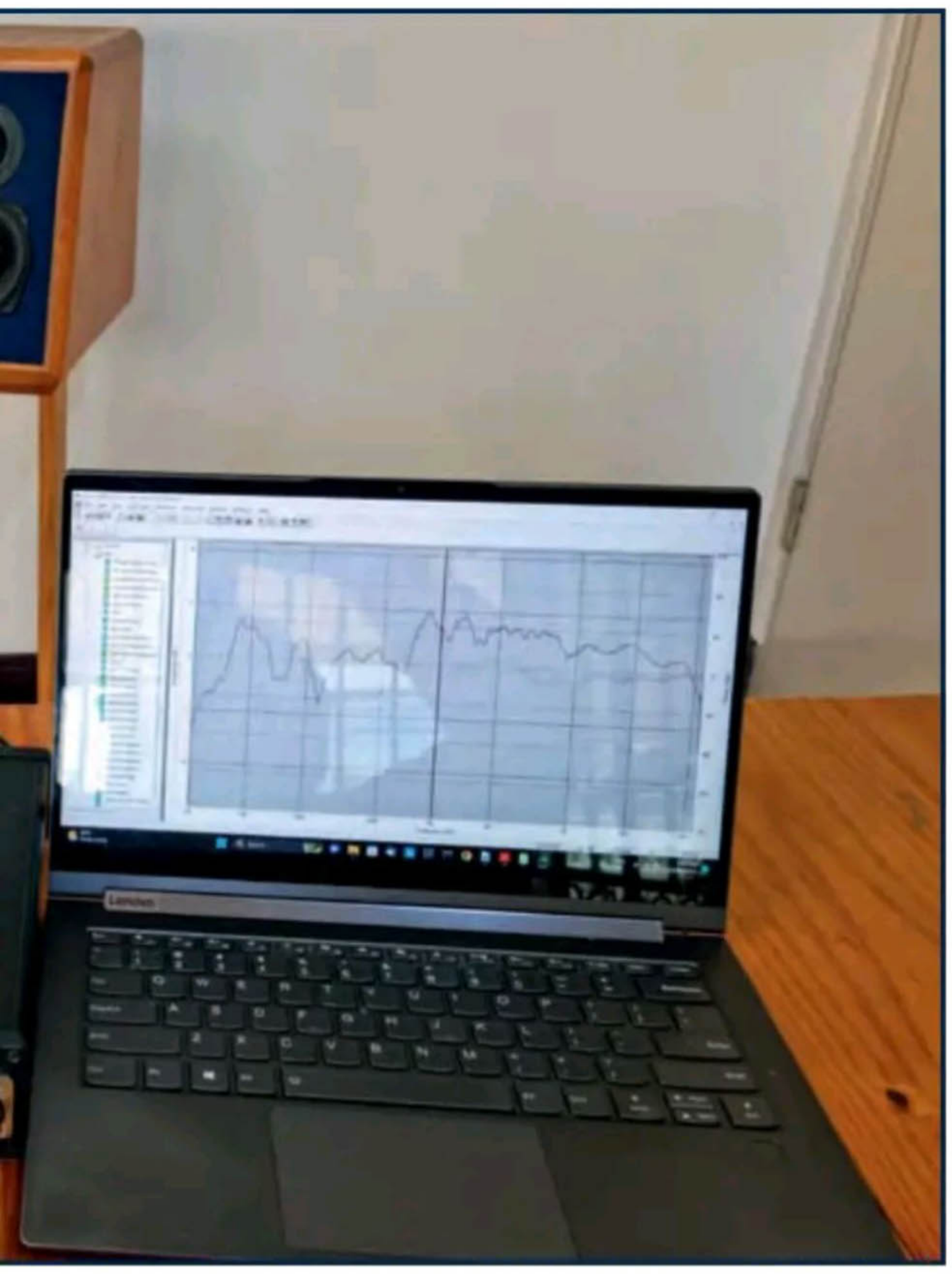
Testing and using it

Using the Calibrated Microphone should be as simple as plugging into a microphone preamplifier that supplies phantom power. We suggest that you check it out before gluing the case shut.

If you don't get a signal on power-up, here are some things to check:

1. Check your solder joints and that you have the PNP and NPN transistors and zener diodes in the right places and with the correct orientations.

2. Apply power by plugging it into the preamp or providing 24-48V DC from a power supply with equal resistors in series with the Hot and



Parts List – Calibrated Measurement Microphone

SMD version – electronic module

1 double-sided PCB coded 01108231, 64 × 13mm

Semiconductors

2 BC860 45V 100mA low-noise PNP transistors, SOT-23 (Q1, Q2)
1 BC849C 30V 100mA low-noise NPN transistor, SOT-23 (Q3)
3 6.8V ¼W zener diodes, SOT-23 (ZD1-ZD3) **[BZX84C6V8]**

Capacitors *(all SMD M2012/0805 50V X7R unless otherwise noted)*

1 100μF 50V radial electrolytic (maximum 8mm diameter)
1 100μF 10V low-ESR radial electrolytic
1 10μF 16V X5R
3 1μF 50V non-polarised SMD electrolytics, 4mm diameter
  [Würth Elektronik 865250640005]
2 2.2nF 5% NP0/C0G
2 1nF 5% NP0/C0G
2 470pF 5% NP0/C0G

Resistors *(all SMD M2012/0805 size 1%)*

2 150kΩ 1 100kΩ 1 39kΩ 1 10kΩ 1 5.6kΩ
2 2.2kΩ 1 1kΩ 1 330Ω 2 47Ω

Through-hole version – electronic module

1 double-sided PCB coded 01108232, 99 × 13mm

Semiconductors

2 BC560 45V 100mA low-noise PNP transistors, TO-92 (Q1, Q2)
1 BC549C 30V 100mA low-noise NPN transistor, TO-92 (Q3)
3 6.8V 400mW or 1W axial zener diodes (ZD1-ZD3) **[eg, 1N754]**

Capacitors

1 100μF 50V radial electrolytic (maximum 8mm diameter)
1 100μF 10V low-ESR radial electrolytic
1 10μF 35V radial electrolytic
3 1μF 63V/100V MKT
2 2.2nF 63V/100V MKT
2 1nF 63V/100V MKT
2 470pF 50V C0G/NP0 ceramic

Resistors *(all axial ¼W 1%)*

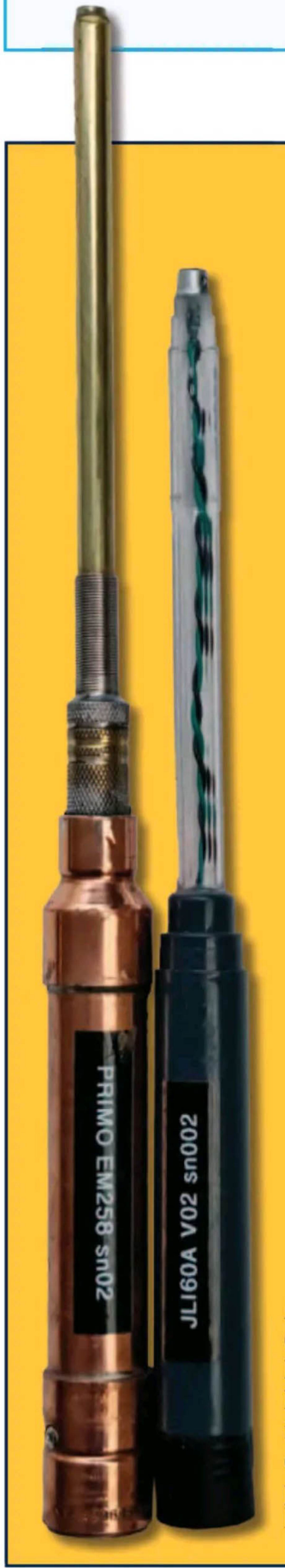
2 150kΩ 1 100kΩ 1 39kΩ 1 10kΩ 1 5.6kΩ
2 2.2kΩ 1 1kΩ 1 330Ω 2 47Ω

Copper-housed version

1 assembled electronic module (SMD or through-hole)
1 ECM capsule with calibration components **[Silicon Chip SC6761-5]**
1 60mm length of 20mm or ¾-inch diameter copper pipe
1 150mm length of >6mm inner diameter brass tube
  (eg, K&S #8132 brass tube) **[hobby shop]**
1 20mm straight capillary coupler **[hardware shop]**
1 20-15mm reducing capillary coupler **[hardware shop]**
1 RCA backshell **[Altronics P0192]**
1 XLR male-male adaptor **[Altronics P0972]**
1 200mm length of 1mm diameter bare copper wire
  (stripped from some spare solid-core mains wire)
1 300mm length of two-way ribbon cable or light-duty figure-8

Plastic pen-housed version

1 assembled electronic module (SMD version)
1 ECM capsule with calibration components **[Silicon Chip SC6761-5]**
1 whiteboard marker **[stationery shop]**
1 ball-point pen with unscrewable ends **[stationery shop]**
1 XLR plug **[Altronics P0823]**
1 300mm length of two-way ribbon cable or light-duty figure-8



Assembled Calibrated Measurement Microphones in both the copper and plastic-type housings.

What is this "Linkwitz Mod"?

Most Electret Condenser Microphones use a FET in a common-source configuration. In this arrangement, the source is connected to the capsule case, and the 2.2kΩ resistor in series with the drain is the load across which the output voltage is generated.

Linkwitz realised that if you can cut between the FET source pin and ground (a track that is accessible on the outside of the capsule), it is possible to rearrange the circuit as a source follower. This gives less gain but a lot more headroom.

We tested it using our mics and found that all the frequency correction parts remain valid. This modification is very fiddly indeed, and it is easy to kill a mic doing this. We feel this is for 'power users' and something you might try once you are confident in making measurements.

There are various references on the internet regarding this. A good place to start is at Siegfried Linkwitz's own web page: www.linkwitzlab.com/images/graphics/microph1.gif

Cold (+ and –) lines. Use 6.8kΩ for a 48V supply or 1.5kΩ for 24V. With this applied:

a. Check the voltage on the microphone side of the resistors. This should be well over 10V, and the voltages should be about equal. If not, check for shorts and correct part locations on the board.

b. Check the voltage across the power supply zener diode, ZD2. It should be close to 6.8V. Check the voltage at the collectors of Q1 and Q2, which should be well above 10V. If not, check the base voltages of these transistors. Also verify that each has a 0.6V base-emitter voltage drop.

c. Check that you have installed R14 fitted (or R8 in if you're using a "Linkwitz Mod" on the ECM) but not both.

d. Check the voltage at pin 2 of CON2, the ECM output for two-wire mode. This should be somewhat less than 6.8V, and if you look with a 'scope, you should be able to see the microphone signal. If not, check that you have the ECM connected the right way around. Also check for shorts on the capsule.

e. If you still have no signal, but the DC voltages at the input and capsule are OK, check the voltage at the base of NPN transistor Q3. This should be about 1.9V, and the voltage on its emitter about 1.3V. The voltage at its collector should be around 3.9V. If these don't make sense, check that you have the right transistor in the circuit.

Using the calibration files

Calibration files for all the ECMs we sell are available for download from the links in the ECM shop items. Your ECM will come in a bag with a number on it. Download the file for that specific type of ECM, then look for the files tagged with that number.

The calibration files match specific capsules. You cannot use them for similar microphones and expect a great outcome.

The file with the FRD extension, starting with your ECM serial number, is in the Speaker Workshop format. You can import it into Speaker Workshop and select it as the microphone calibration. This file contains 4096 rows with Frequency, Gain and Phase figures (the Phases are set to zero). Load this, and you are all set!

0dB in the calibration files equals -40.3dBV/Pa. Given that 1Pa is 94dB SPL, that means that 0dB is 53.7dB SPL. Happy measuring. **PE**

Silicon Chip Kits & Capsules

SC6755 SMD Kit
Includes the PCB and all onboard parts besides the XLR socket.

SC6756 Through-Hole Kit
Consists of the PCB and all onboard parts besides the XLR socket.

SC6761/2/3/4/5 ECMs
See Table 1 for the various options. Each comes with the required SMD compensation components, as shown in Table 2. If building the through-hole version, you can source the compensation components (resistors & MKT or greencap capacitors) from your local electronics shop.

Photo 4: the SMD board fits a treat into the whiteboard marker case after it has been stripped apart and cleaned out. The XLR connector will need the tab cut off with side cutters to allow you to solder to the PCB.

JLI60A V02 sn002

Photo 5: the assembled Biro-cased Microphone, ready to have the ECM pulled in and glued to the tip.

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46%
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Meet New Cybersecurity Mandates Easily: PIC32CK SG MCU

Arm® Cortex®-M33 Core With HSM and TrustZone® Technology

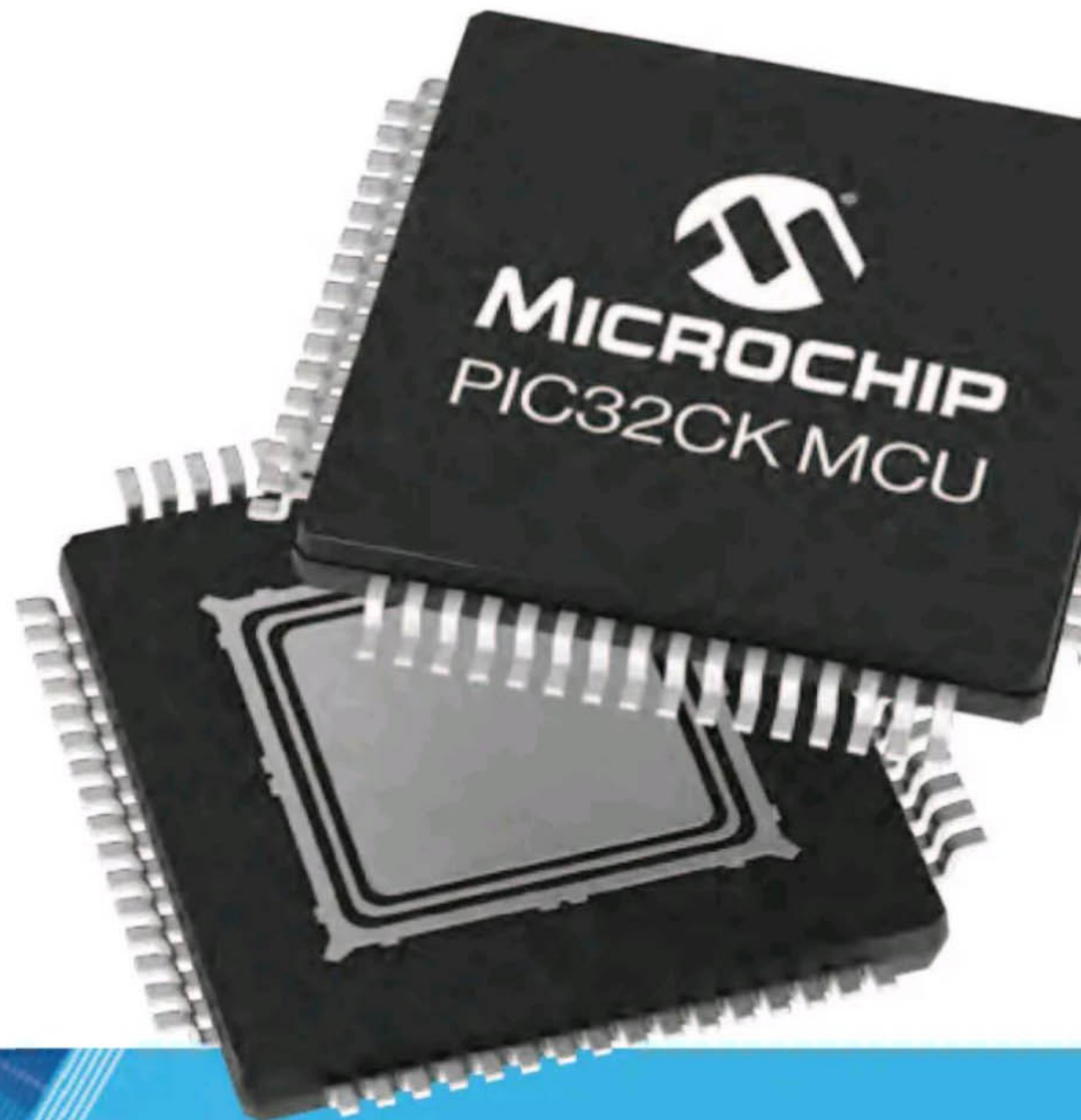
In anticipation of stringent cybersecurity standards, our PIC32CK SG MCU is your solution for addressing the pressing cybersecurity challenges without compromising performance.

The PIC32CK SG MCU family combines the security of a fully isolated Hardware Security Module with Arm's TrustZone® secure partitioning. This provides defense in depth against cyber-attacks for the most demanding applications.

Designed as a mid-range MCU, the PIC32CK SG MCU integrates advanced hardware security subsystems to surpass regulatory requirements effortlessly. With a high level of cyber protection integrated, designers can ensure their products meet and exceed cybersecurity mandates without sacrificing efficiency or speed.

Key Features

- Based on Cortex-M33 at 120 MHz
- 2 MB Dual Panel Flash/512 KB RAM for complex system
- 10/100 Ethernet, USB, CAN-FD, I2S, I2C
- Advanced key management
- Certificate authority
- Secure boot



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MEC2572A-UK-06-24

GND VCC SCL SDA

Using Electronic Modules with Jim Rowe

1.3-inch (33mm) Monochrome OLED Display

Small monochrome OLED display modules have become widely available at a low cost in the last few years. Typically these measure only about 35×33mm but offer a 128×64 pixel resolution in a few different colours, like white or blue. Their I²C serial interface means that popular microcontrollers can easily drive them.

OLEDs (organic light-emitting diodes) are solid-state light-emitting devices like standard LEDs. But instead of using a regular semiconductor P-N junction to emit light when passing a current, an OLED uses a thin film of an organic compound. As a result, displays using OLEDs tend to be thinner, lighter and use significantly less energy than those using traditional LEDs.

In the last 15 or so years, they have become widely used in smartphones, handheld gaming consoles and, more recently, colour TVs.

Small monochrome OLED displays are also used extensively in portable electronic equipment, so they have dropped significantly in price. Among the most popular are the 1.3-inch (33mm) modules, such as the one shown in the photos.

We have already used these in a couple of projects, like the Multi-Stage Buck/Boost Charger Adaptor from October 2023.

These are available from a wide range of online suppliers, including via eBay, AliExpress and Amazon. Prices vary over a pretty wide range, about £3 up to nearly £10 from overseas suppliers, not including postage or packing.

They are also sold in the Silicon Chip Online Shop for AU$15 + P&P (around £8), with catalog codes of SC5026 (blue display) and SC6511 (white display).

These are not the smallest OLED modules available. Another common size is 0.96in or 24.4mm diagonal, with prices slightly lower than those for the 1.3in/33mm modules. These generally have the same display resolution; the smaller size means those

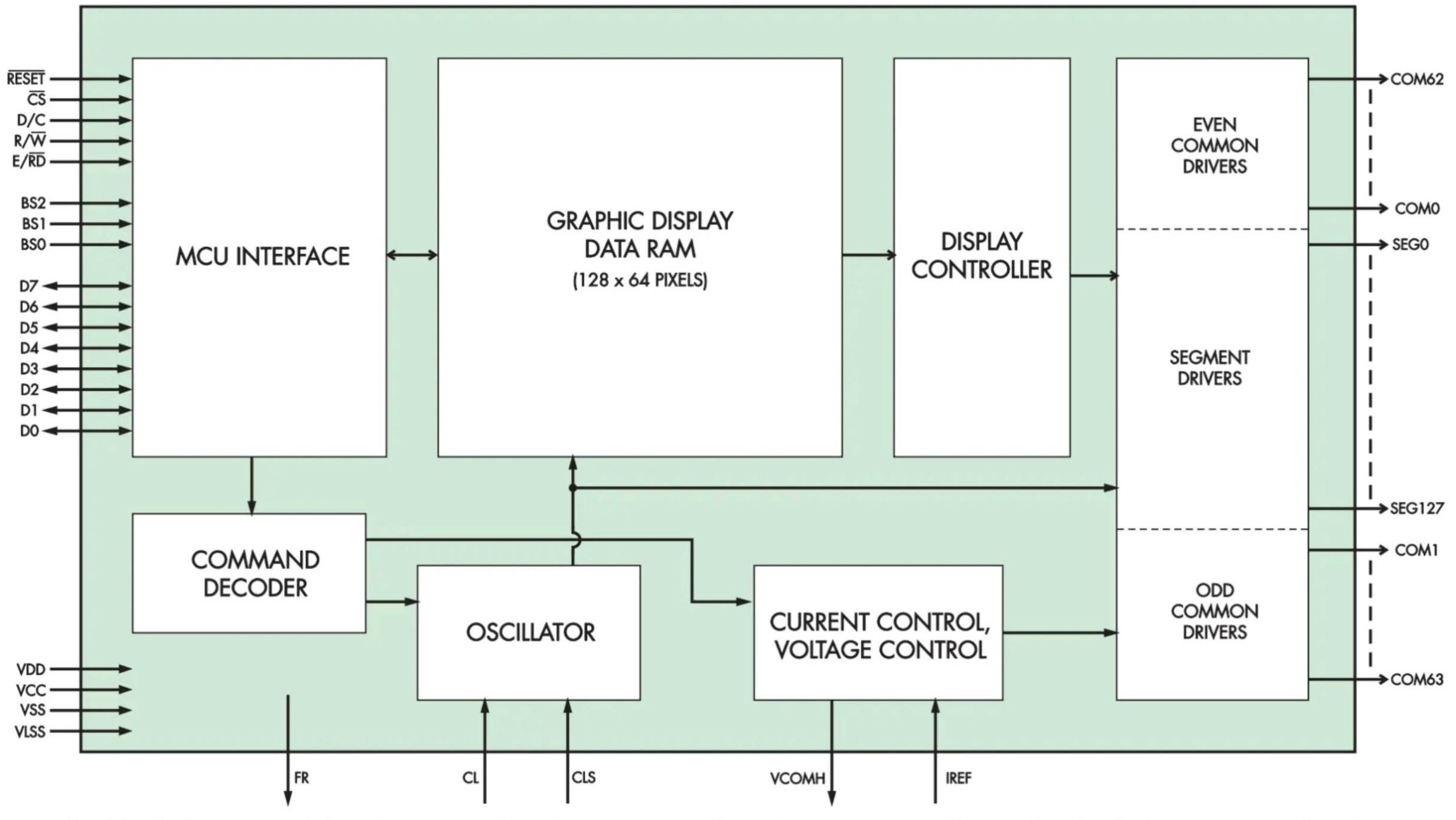

RESET
CS
D/C
R/W
E/RD
BS2
BS1
BS0
D7
D6
D5
D4
D3
D2
D1
D0
MCU INTERFACE
GRAPHIC DISPLAY DATA RAM
(128 x 64 PIXELS)
DISPLAY CONTROLLER
EVEN COMMON DRIVERS
SEGMENT DRIVERS
ODD COMMON DRIVERS
COM62
COM0
SEG0
SEG127
COM1
COM63
COMMAND DECODER
OSCILLATOR
CURRENT CONTROL, VOLTAGE CONTROL
VDD
VCC
VSS
VLSS
FR
CL
CLS
VCOMH
IREF

Fig.1: the block diagram of the SH1106 and SSD1306 controllers that are typically used in both the 0.96in and 1.3in OLED modules.

pixels are smaller. We used these in a few recent projects, like the Advanced Test Tweezers (February & March 2024).

There are also even smaller OLED modules, like those with a designated size of 0.49in/12.45mm. Those have a lower display resolution of 64×32 pixels. We used those in the original SMD Test Tweezers from the October 2022 issue.

Inside the OLED modules

The 1.3in OLED modules all use a single interface/controller and OLED driver IC, usually the SH1106 from Sino Wealth or the SSD1306 from Solomon Systech. The same controllers are used in the 0.96in modules.

Fig.1 is a block diagram of the SH1106 and SSD1306 controllers. At upper left is the microcontroller (MCU) interface, which can be configured to interface with an MCU via an 8-bit 6800/8080-series parallel interface, a 3/4 wire SPI interface or an I^{2}C serial interface. Most 1.3in and 0.96in OLED modules use the last option, I^{2}C.

Received display data is stored in the graphic display data RAM (the large block to the right of the interface), while commands are sent to the command decoder block at lower left. The display controller block at upper right uses the display data to drive the columns and segments of the OLED via the common and segment drivers shown at far right.

The OLED has 64 common/column lines and 128 segment lines, matching the 128×64 pixel resolution.

There are commands to update the display, turn the OLED display on or off, set the OLED addressing mode, set the column starting address, and adjust the OLED's display contrast/brightness (which also determines its operating current).

The SH1106 and SSD1306 devices both come in very thin (0.3mm) SMD packages with over 260 contact pads. In the modules, they are mounted on the rear of the OLED screen itself.

The module circuit

Fig.2 is the circuit of a typical 1.3in monochrome OLED module based on the SH1106 device (those using the SSD1306 are very similar). The OLED is at upper right, with the SH1106 interface/display RAM/controller/driver IC1 in the centre. The rest of the circuit (to the left of IC1) provides the module's power supply and I^{2}C input interface.

Four-pin SIL header CON1 is used for both power input and the I^{2}C interface. REG1 takes the incoming V_{CC} (typically around 5V) and steps it down to +3.3V to run both IC1 and the OLED. The +3.3V line also drives IC1's reset circuit (it needs to be reset as soon as power is applied) and feeds the 4.7kΩ pullup resistors for the I^{2}C interface lines, SCL and SDA.

The SH1106 and the SSD1306 controllers can adopt an 8-bit I^{2}C address of either 0x78 or 0x7A, depending on the voltage applied to the DC input at pin 15. If the pin is pulled to ground (in this case, via a 4.7kΩ resistor), the controller adopts the 0x78 address, while if the pin is pulled up to +3.3V, it responds to the 0x7A address. That lets you run two similar OLED modules on the same I^{2}C interface.

Most of the modules are set for the 0x78 address when you get them, but it is relatively easy to swap the 4.7kΩ

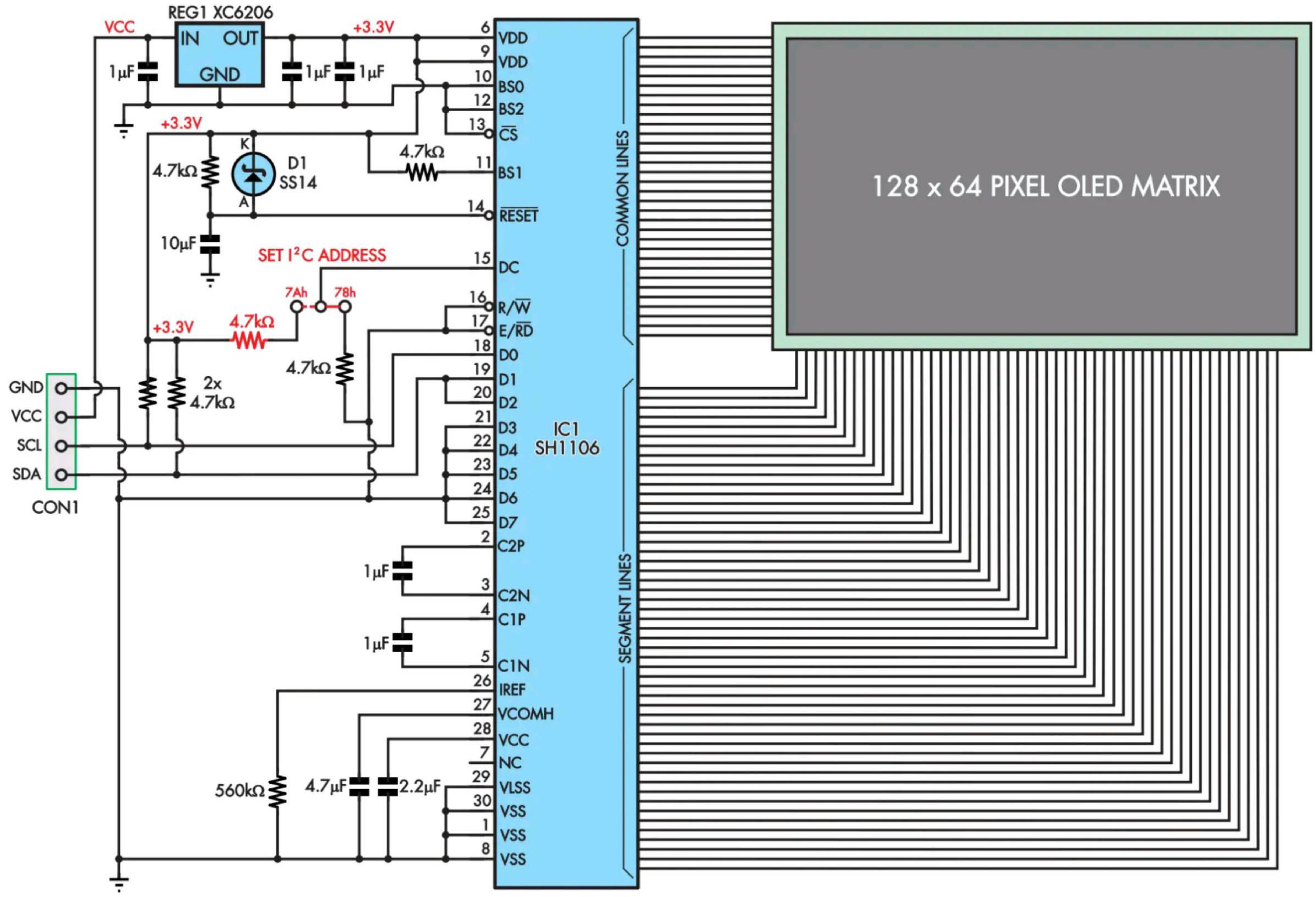
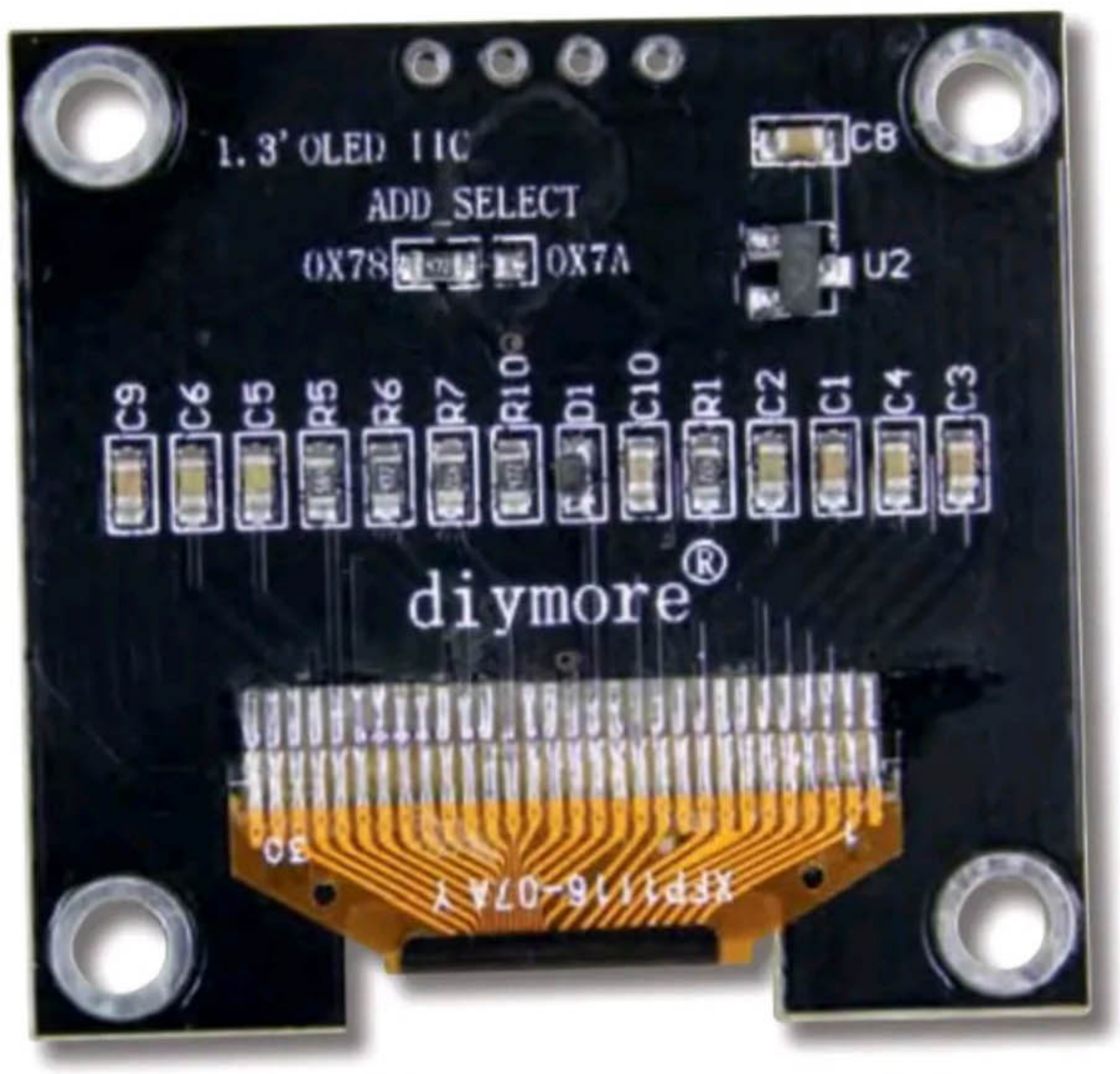

REG1 XC6206
IN
OUT
GND
VCC
+3.3V
1µF
1µF
1µF
+3.3V
K
D1
SS14
A
4.7kΩ
4.7kΩ
10µF
SET I²C ADDRESS
7Ah
78h
+3.3V
4.7kΩ
4.7kΩ
2x
4.7kΩ
GND
VCC
SCL
SDA
CON1
6 VDD
9 VDD
10 BS0
12 BS2
13 CS
11 BS1
14 RESET
15 DC
16 R/W
17 E/RD
18 D0
19 D1
20 D2
21 D3
22 D4
23 D5
24 D6
25 D7
2 C2P
3 C2N
4 C1P
5 C1N
26 IREF
27 VCOMH
28 VCC
7 NC
29 VLSS
30 VSS
1 VSS
8 VSS
1µF
1µF
560kΩ
4.7µF
2.2µF
IC1
SH1106
COMMON LINES
SEGMENT LINES
128 x 64 PIXEL OLED MATRIX

Fig.2: the circuit diagram of the 1.3in OLED module with a SH1106 controller. The circuitry separate to the OLED matrix and controller is for providing power and the I^{2}C interface.


1.3' OLED IIC
ADD_SELECT
0X78
0X7A
CB
U2
C9 C6 C5 R5 R6 R7 R10 D1 C10 R1 C2 C1 C4 C3
diymore®
30
XFP1116-07A Y

The rear of the 1.3in OLED module shown at twice actual size.

resistor over to the 'pullup' position to change the address to 0x7A if needed.

Some 1.3in OLED modules have a 7-pin interface header instead of the 4-pin header shown in Fig.2. These modules allow the use of the faster SPI interface instead of the I²C interface we're focusing on here.

Now let's focus on what is involved in driving one of these modules from an MCU like an Arduino Uno or Micromite.

Connecting it to an Arduino

Connecting a 1.3in OLED module to an Arduino Uno is relatively straightforward, as you can see from Fig.3. The GND and V_{CC} pins connect to the GND and 3.3V pins on the Arduino, while the SCL and SDA pins connect to the Arduino's A5 (SCL) and A4 (SDA) pins, respectively.

If using an Arduino Mega 2560, the arrangement is similar, but the module's SCL pin goes to pin 21 of the 2560 and the SDA pin to the 2560's pin 20.

As for software support, if you go to the Arduino website and look at the library listings for "Display" applications (pemag.au/link/abl7), you will find quite a few libraries to do this job: Adafruit SSD1306, GyverOLED, OLED SSD1306-SH1106, OLED Display VGY12864L-03, ss_oled, ssd1306, ssd1306xled and U8g2.

Another site (www.lcdwiki.com) offers a library called "1.3inch_IIC_OLED_Module_SKU:MC130VX", together with some documentation and three example sketches. All of these depend on the library U8g2, which you can download as a zip file from https://github.com/olikraus/

The three example sketches demonstrate how to draw graphics, text strings and a BMP image on the OLED, so they're pretty informative. Screens 1 to 5 show some of the displays I was able to produce using these sketches and a blue 1.3in OLED module.

Connecting it to a Micromite

Connecting one of the 1.3in OLED modules to a Micromite MCU is also quite easy. Fig.4 shows the connections needed for driving the OLED module from a Micromite Plus Explore 64 (August 2017).

Connecting the module to a Micromite Mk2 or LCD Backpack V1/V2/V3 would be almost the same, except the module's SCL pin would be connected to pin 17 of the Micromite and the SDA pin to pin 18.

As with an Arduino, you need to install some software to let the Micromite drive the OLED module. That isn't quite as easy as with the Arduinos, as there is no widely available Micromite OLED driver software yet.

Still, because I knew that some Silicon Chip readers would want to drive an OLED module from a Micromite, I decided to try writing an MMBasic program to go through the necessary steps.

Luckily, fellow Silicon Chip staff member Tim Blythman was able to offer some help, as he has done quite a bit of work with the smaller 0.96in OLED modules (which use the same SH1106 and SSD1306 chips) and is very familiar with the steps needed to drive them.

Thanks to Tim's help, despite losing some of my rapidly thinning grey hair, I was able to develop an MMBasic program that can drive one of these OLED modules from a Micromite. It demonstrates how text and simple graphics can be displayed on its screen. The program is called "OLED MODULE TEST Prog2.bas", and the display it

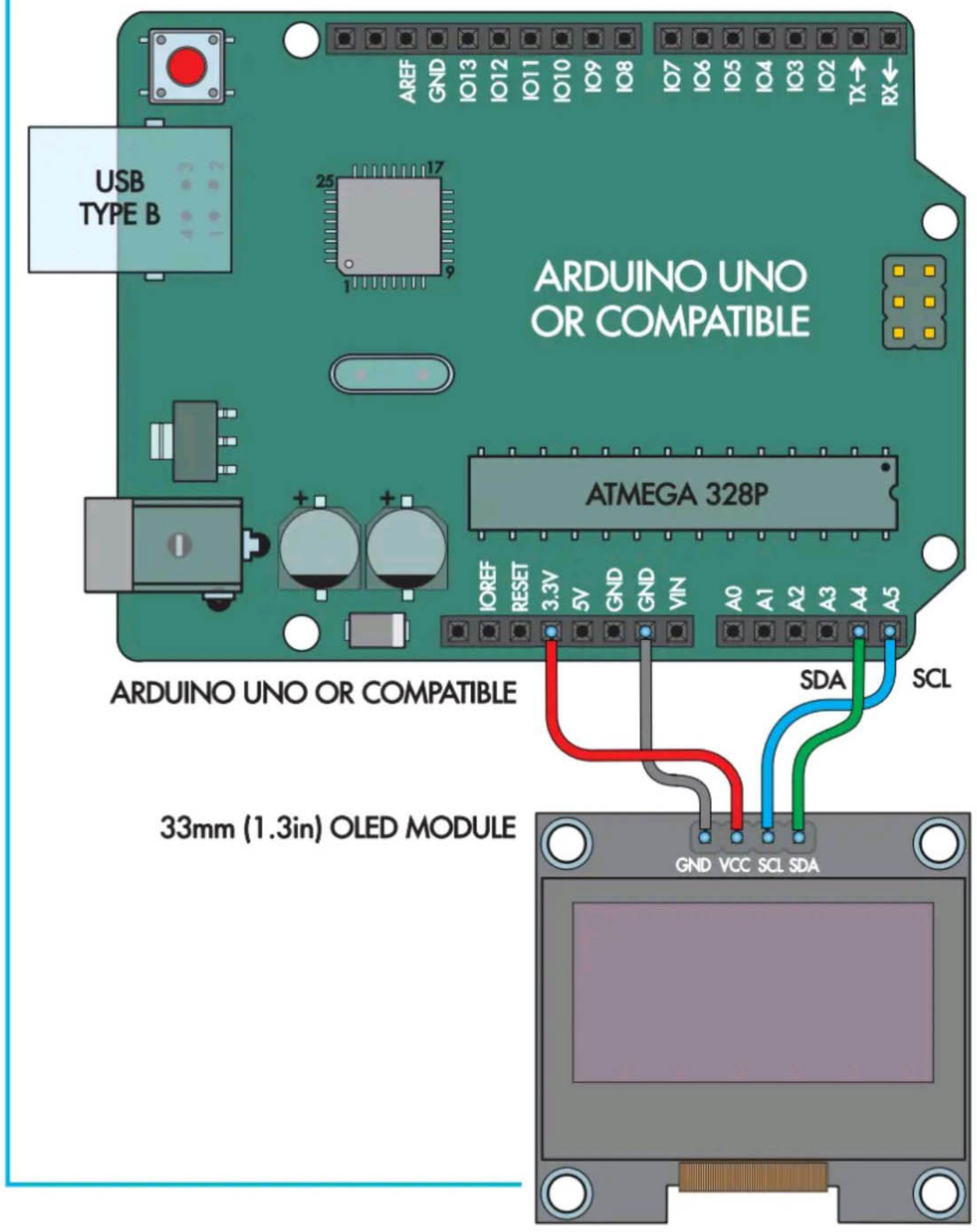
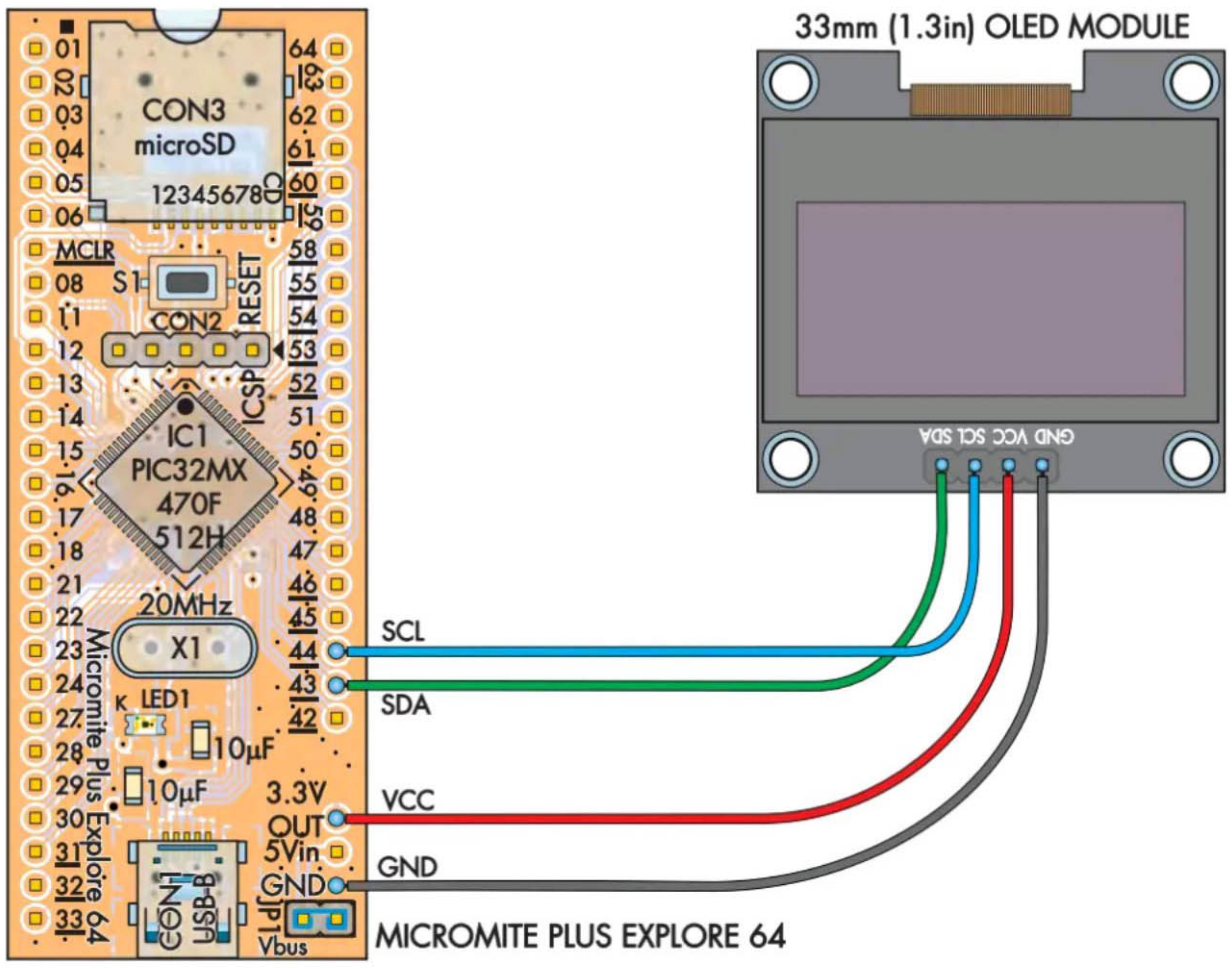
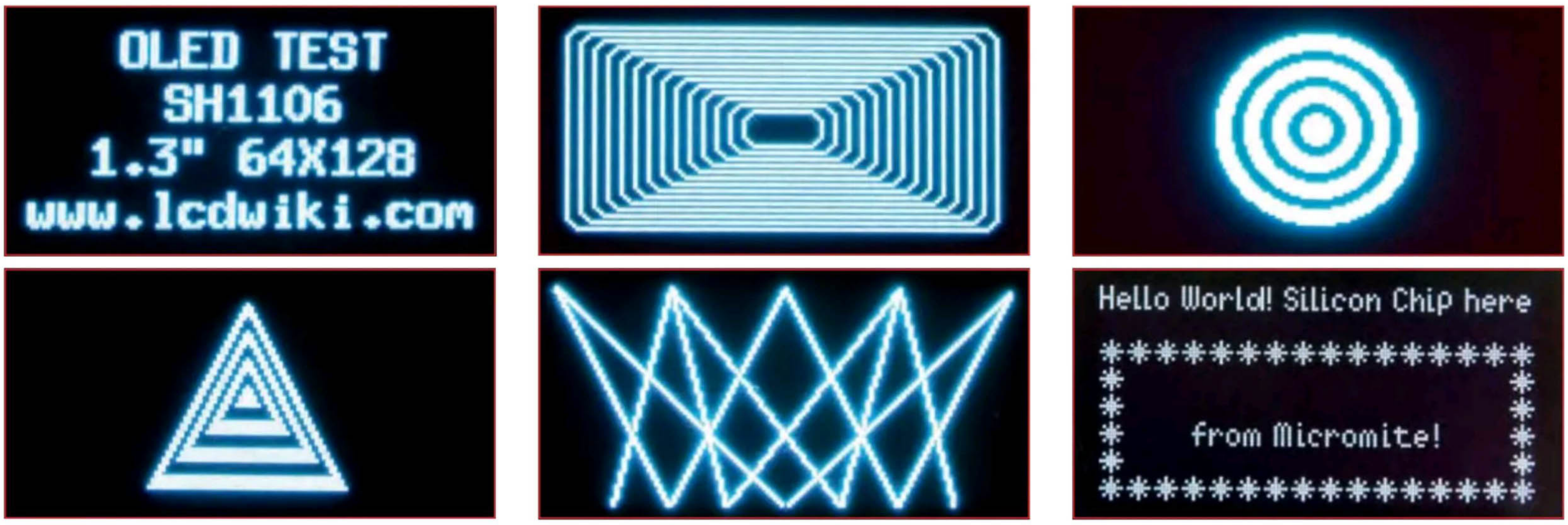

AREF GND IO13 IO12 IO11 IO10 IO9 IO8 IO7 IO6 IO5 IO4 IO3 IO2 TX→ RX←
USB TYPE B
ARDUINO UNO OR COMPATIBLE
ATMEGA 328P
IOREF RESET 3.3V 5V GND GND VIN A0 A1 A2 A3 A4 A5
SDA
SCL
ARDUINO UNO OR COMPATIBLE
33mm (1.3in) OLED MODULE
GND VCC SCL SDA

Fig.3 (left): you can use this diagram to help connect a 1.3in OLED module to an Arduino Uno or similar.

Fig.4 (below): how to drive the OLED module via a Micromite Plus Explore 64. You can similarly connect it to a Micromite BackPack by connecting SCL to pin 17 and SDA to pin 18.


CON3
microSD
12345678
MCLR
S1
CON2
RESET
ICSP
IC1
PIC32MX
470F
512H
20MHz
X1
LED1
10µF
10µF
3.3V OUT
5Vin
GND
CON1
USB-B
Vbus
Micromite Plus Explore 64
SCL
SDA
VCC
GND
MICROMITE PLUS EXPLORE 64
33mm (1.3in) OLED MODULE
GND VCC SCL SDA



Screens 1-6 (left-to-right, top-to-bottom): example output produced by the various test programs we downloaded or created for use with the 1.3in (33mm) OLED module. Screen 6 at lower right is from our Micromite program.

achieves is shown in Screen 6.

It's a pretty basic little program (no pun intended), and as it stands, it only demonstrates how the OLED module can display text and simple graphical symbols. It doesn't let you type text in via the Micromite console and display it directly on the OLED; that would involve additional programming.

That's because the easiest way to drive these OLEDs is by setting the driver chip to Page Addressing Mode, which effectively divides the OLED screen into eight horizontal 'pages', each page consisting of 128 vertical segments eight pixels high.

The pages are arranged vertically, with page 0 along the top of the screen, page 1 immediately below it and then the remaining pages descending until page 7 runs along the bottom of the screen, as shown on the left side of Fig.5.

When the driver chip updates each page on the OLED (which it does one page at a time), it starts at the far left and displays the eight-pixel segments one after the other, moving from left to right. Each eight-pixel segment is sent in b0 to b7 order ('LSB-first'), as shown on the right-hand side of Fig.5.

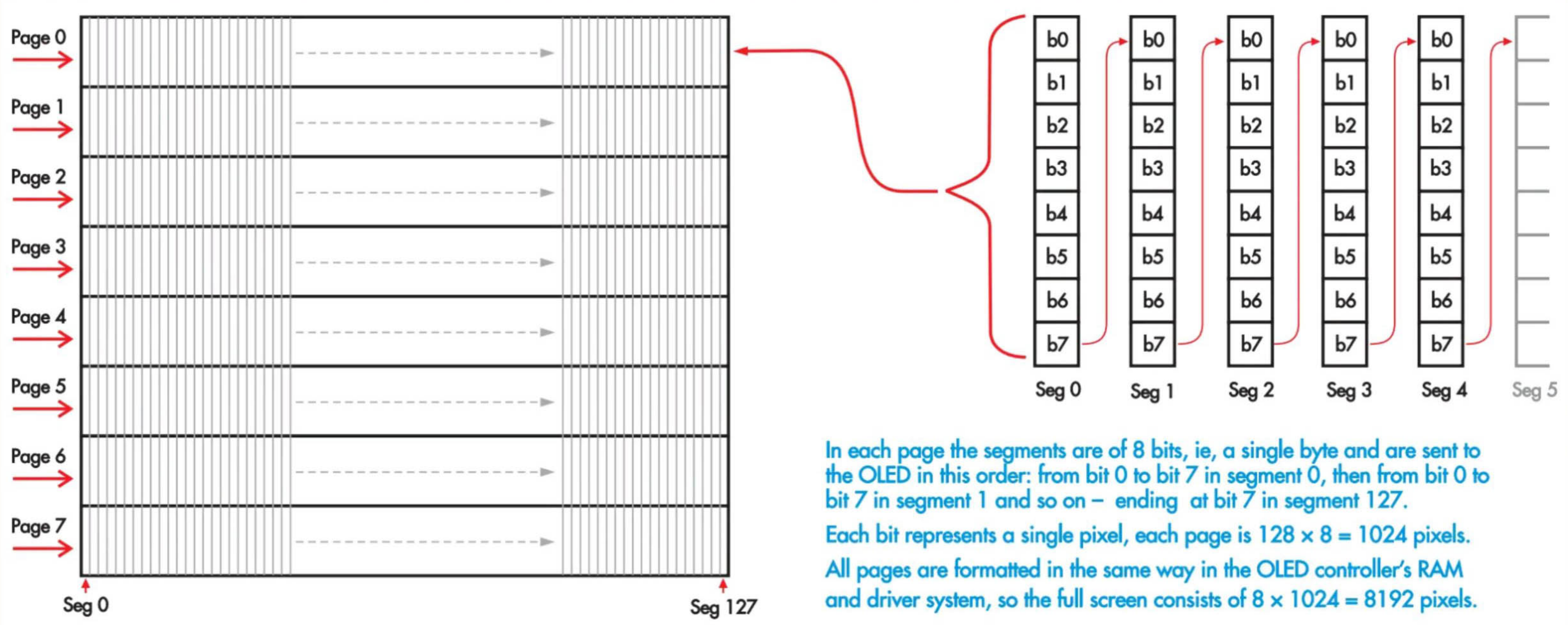
This Page Addressing Mode makes it not too difficult to display lines of text; all you need to do is work out the sequence of segment bytes required to show the character or symbol you want to display, then send that sequence to the OLED controller as a sequence of single bytes. For text, it's easiest to have a line spacing of 8 pixels, meaning the characters are around 7 pixels tall and perhaps 4-5 pixels wide.

To help you do this, I have worked out the byte sequences for the upper case and lower case text characters, plus the basic numerals (0 to 9) and a reasonable number of common symbols. These are listed in a second dummy MMBasic program called "OLED MODULE textchar strings.bas", which you can download from the Silicon Chip website along with "OLED MODULE TEST Prog2.bas".

That should allow you to write a program that can display up to eight lines of text on the screen of one of these 1.3in OLED modules.

Drawing detailed graphics on the OLED screen is a bit more involved but, as the demonstration program shows how to write pixels into the OLED's display RAM, that should provide a starting point for more advanced graphics.

A reader with more programming experience might accept the challenge of creating a full display driver for these OLEDs, possibly based on the starting point I have provided.



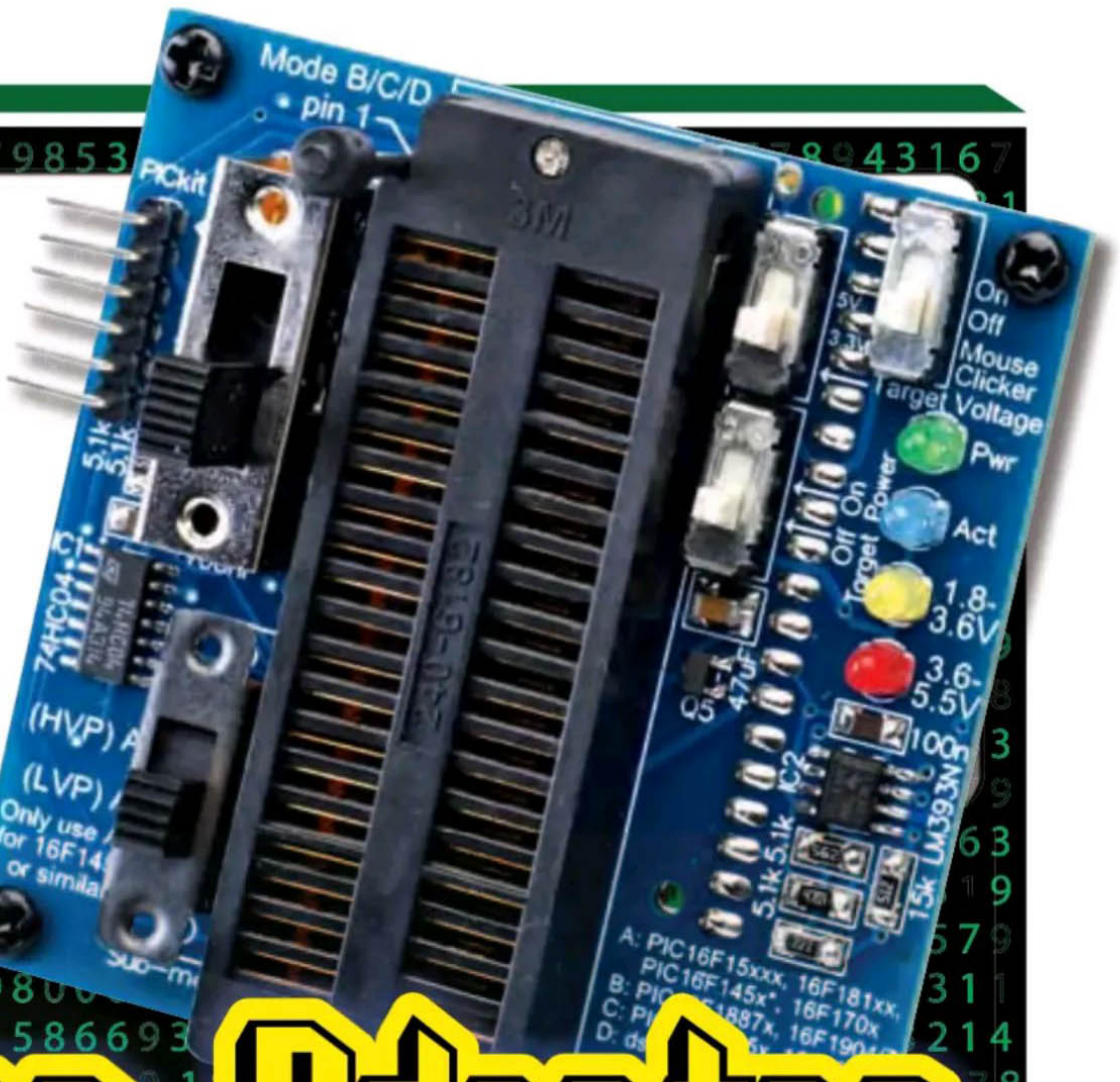
In each page the segments are of 8 bits, ie, a single byte and are sent to the OLED in this order: from bit 0 to bit 7 in segment 0, then from bit 0 to bit 7 in segment 1 and so on – ending at bit 7 in segment 127.

Each bit represents a single pixel, each page is 128 × 8 = 1024 pixels.

All pages are formatted in the same way in the OLED controller's RAM and driver system, so the full screen consists of 8 × 1024 = 8192 pixels.

Fig.5: Page Addressing Mode divides the OLED into eight sections as shown. This is the easiest way to drive the OLED.

This small, low-cost adaptor lets you program most newer PIC microcontrollers out-of-circuit. It works in conjunction with a PICkit or SNAP in-circuit programmer and provides five different modes to suit a range of chips from eight to 40 pins. It can even be used with SMD chips in SOIC, SSOP or TSSOP packages.



Nicholas Vinen's

PIC Programming Adaptor

This new programming adaptor board is compact, easy to build and suits a large range of PICs released in the last 5-10 years, including many that we use in our projects.

As we sell programmed PICs (and other microcontrollers) to build the projects described in our magazine, we have a box full of programming sockets, adaptors and other rigs to suit the many different types of chips. Lately, I realised that most of the time, we were using just a few of those adaptors because we have transitioned to mainly using recent PICs (released in the last 5 years or so).

However, we still have to switch between several rigs because recent PICs still use a few different pinouts. For example, many of the latest 8-bit PICs use one configuration, while PIC24s, dsPICs and PIC32s use another. Some larger (eg, 40-pin) 8-bit PICs use further configurations.

We previously published a fairly comprehensive PIC & AVR programming adaptor in the May & June 2013 issues.

While we still use that board quite often, it was geared towards the chips that were available back then, and things have changed substantially. Because it had to support so many different pinouts, it had certain compromises this newer design doesn't have to deal with.

Uses and function

You may not need this board if you always design or build boards with in-circuit serial programming (ICSP) headers.

However, there are times when it is convenient to program a chip out of circuit; for example, if your board is so compact that there's no space for an ICSP header, or you want to swap chips out in the field. Or, like in our case, you want to supply someone with a pre-programmed chip.

You can build individual programming jigs for each type of chip – which is what we did – but it can be annoying. You end up with many that you must dig through to find the right one each time. With this board, you just flick a few switches and it's ready to program various chips.

Fig.1 shows the five different pin configurations it offers. Each is colour-coded; the labels with that colour in the background indicate the function assigned to that socket pin in that mode.

There are two settings for mode A and one for modes B, C and D. The two A modes suit almost all modern 8-bit PICs, which are inserted with the pin 1 end at the bottom of the ZIF socket. These all use the same pins for VDD, GND and MCLR and mostly use the

Features & Specifications

- Adapts an in-circuit programmer like the Microchip PICkit or Snap to a ZIF socket
- Can deliver 3.3V or 5V to the target; target power can also come from the programmer (if supported)
- Programs DIP chips directly or SMD SOIC/SSOP/TSSOP via low-cost adaptors
- PTC protection for the device being programmed (eg, in case it's inserted in the socket incorrectly)
- Supports most newer 8-bit PICs and most 16-bit and 32-bit PICs (including PIC24, dsPIC, PIC32MM and PIC32MX) with 8-40 pins
- Tested PICs include 16F15213/4, 16F15323, 16F18146, 16F18857, 16F18877, 16(L)F1455, 16F1459, 16F1709, dsPIC33FJ256GP802, PIC24FJ256GA702, PIC32MX170F256B and PIC32MX270F256B
- Many more chips are supported than listed above
- LEDs indicate source power present, target power present, voltage range and programming activity
- Simple to use with just five switches and silkscreened instructions
- Includes 'mouse clicker' option to automatically trigger programming when the target is powered

same pins for programming (PGD = data and PGC = clock).

The exception is devices with more than eight pins, like the PIC16(L)F1455 and PIC16(L)F1459, which can use the same programming pins as the other devices – shown in red in Fig.1 – but only for low-voltage programming (LVP). Sometimes, low-voltage programming is disabled. In that case, you must use mode A2, via the mauve labelled pins.

Also, LVP could be disabled once you program them, so you might need to use the alternative mode for reprogramming.

Not all chips support programming on those pins (especially 8-pin devices, which don't extend that far!), so we can't always use the alternative pins. Hence we use a dedicated switch to select between the two A modes. A separate four-throw switch selects between the A, B, C and D modes.

In B, C and D modes, pin 1 is placed at the top of the ZIF socket.

Mode B is for a few of the larger (40-pin) 8-bit PICs that use a different pinout than provided in mode A for backwards compatibility with certain older chips like the PIC16F877 (you can use mode B to program those older chips too). One example of a newer chip that needs mode B is the PIC16F18877 that we've used in a couple of projects, such as the USB Cable Tester (November & December 2022).

Somewhat annoyingly, the 28-pin version of that chip, the PIC16F18857, cannot be programmed in mode B because its supply pins are in different locations (again, likely for backwards compatibility). So mode C leaves PGD, PGC and $\overline{\text{MCLR}}$ in the same places as mode B but changes VDD and GND to suit those chips.

Finally, mode D suits a very common pinout used by many 28-pin devices, including much of the 16-bit PIC24 range, the 16-bit dsPIC range and the 32-bit PIC32MX range. We've opted to use pins 4 and 5 as PGD and PGC, respectively; many of these chips support multiple different (usually three) sets of programming pins, but this pair (#1) is the most consistently supported.

The only other slightly unusual thing about mode D is that, in addition to connecting PGD, PGC, $\overline{\text{MCLR}}$, VDD and GND to various pins, a high-value, low-ESR capacitor also needs to be connected between pin 32 (pin 20 on the 28-pin chip) and GND. This board connects a 47µF ceramic capacitor through a low-resistance Mosfet to provide that function.

One advantage of this circuit compared to the 2013 Programming Adaptor is that because modern PICs mostly use one of just a few pinouts, we only need four modes, making the switching considerably simpler. That means shorter paths between the ICSP socket and the ZIF socket pins and fewer components connected to those pins.

As a result, programming is more reliable and programming speeds are higher. The older Adaptor sometimes requires you to reduce the programming speed to "slow" for it to work, but this new Adaptor generally works at "normal" and even "fast" programming speeds.

Circuit details

The full circuit is shown in Fig.2. It looks complicated but isn't hard to understand if you break it into chunks.

All of the switching for $\overline{\text{MCLR}}$ (which also sometimes carries VPP, the high programming voltage), PGD (data) and PGC (clock) is done by four-pole, four-throw slide switch S1. S1a switches $\overline{\text{MCLR}}$ from the ICSP header (CON1) to the appropriate pin on SK1 for each mode, with mode A at the top and mode D at the bottom.

Similarly, S1b switches PGD (data) and S1c switches PGC (clock) to the pins of SK1. Thus, the only components in the path of these programming signals are CON1, SK1, S1 and some short PCB tracks, minimising signal degradation. One exception is that the PGC/PGD signals also pass through switch S2 in mode A, providing the two sub-modes, but the tracks connecting it to SK1 are very short.

The fourth pole of S1, S1d, handles all the power pin switching (plus VCAP). It does this by grounding one of the four remaining switch pins.

For pins that need VDD applied in this mode, that switch terminal connects to the gate(s) of P-channel Mosfet(s) with a shared gate pull-up resistor. So when that terminal is grounded, the gates are pulled to ground, giving them a negative gate-source voltage and switching them on. In other modes, the resistor pulls up the gate(s), and they switch off, no longer driving those pins.

For pins that need GND applied in a specific mode, the grounded pole is connected to the gate of one of the six inverters within IC1, a 74HC04 hex CMOS inverter (with a pull-up resistor, if one is not already present).

The inverter's output goes high when that pole is selected (pulling its input low), and that high level drives the gate(s) of one or more N-channel Mosfet(s), pulling the appropriate ZIF socket pins to GND.

The only variations from this scheme are when multiple modes need to drive the same pin. In this case, diode logic is used to send the right voltages to the Mosfet gates. For example, dual diode D2 is configured so that input pin 9 of IC1d goes low in mode C or D. That causes IC1d's output pin 8 to go high, switching on Q3, which pulls SK1's pin 8 low.

There are 100nF capacitors throughout the circuit connected between socket power pins via the switching Mosfets. That is, they connect between the source pins of the

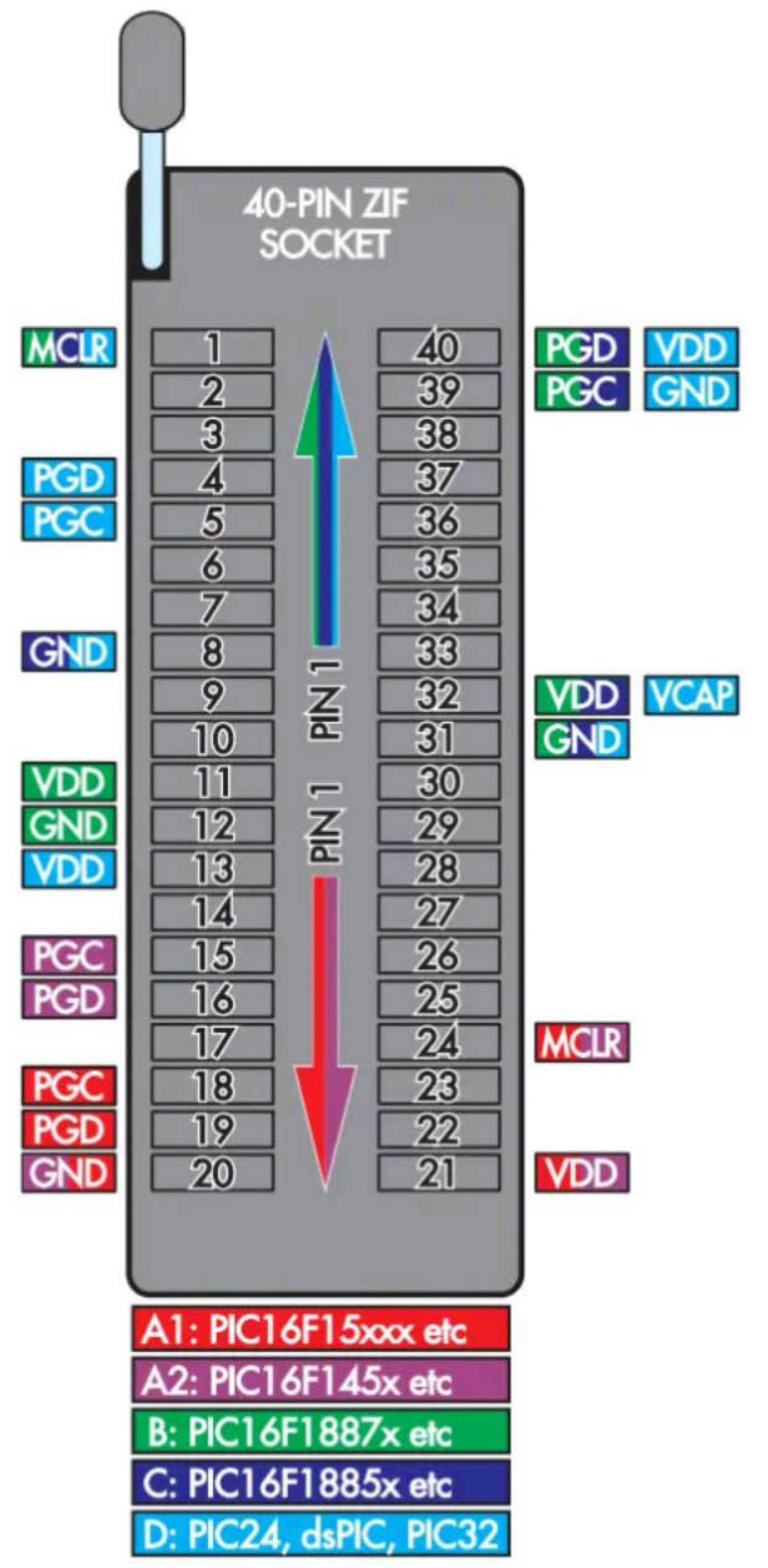
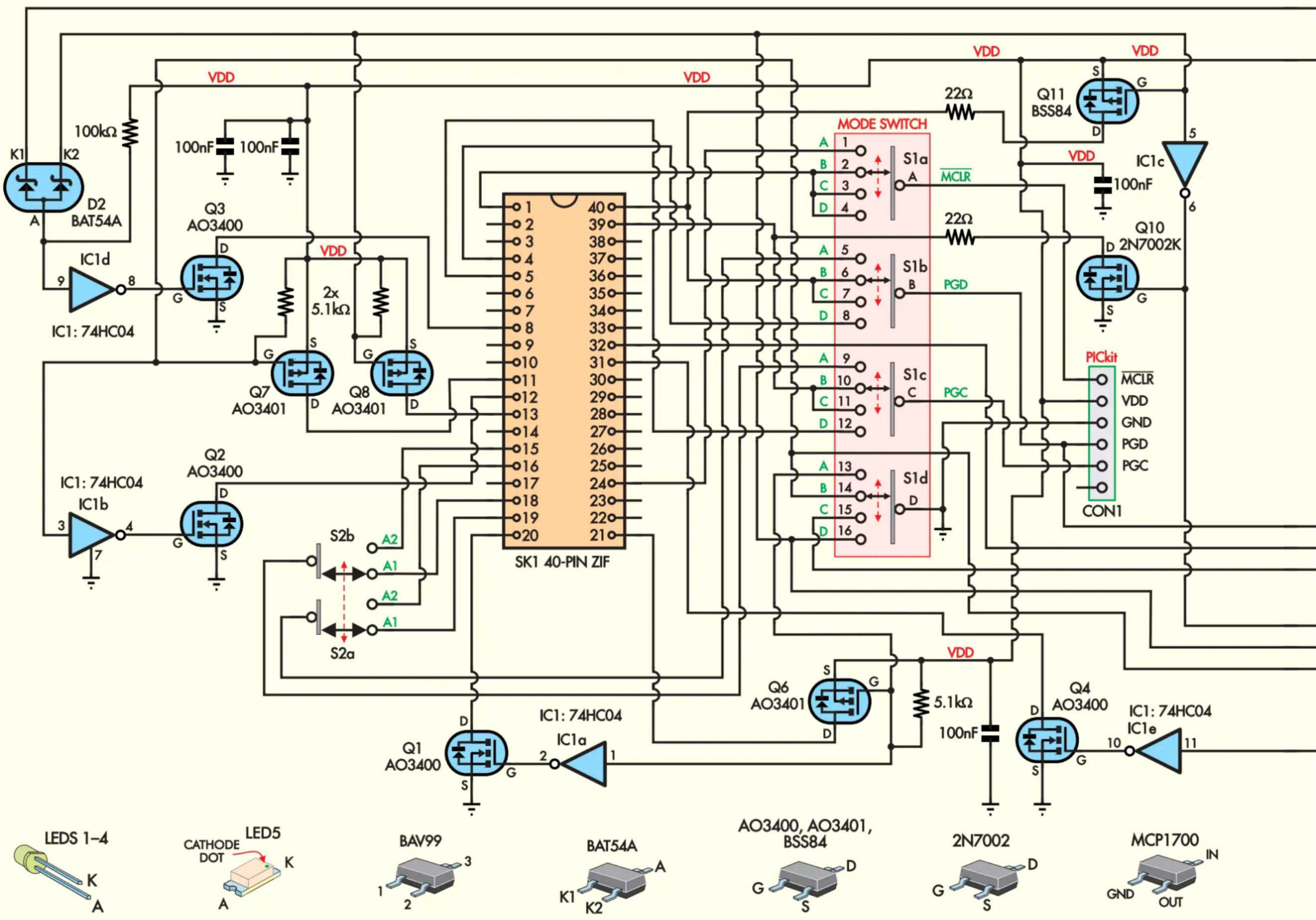


Fig.1: this shows how the five programming pins are mapped from the serial programmer to the ZIF socket in each mode; pin 1 is at bottom right for modes A1 & A2 and upper left for the others. Some pins have the same function in multiple modes, where the background colour is split between two or three modes. The only pins with different roles in different modes are 32, 39 & 40.


VDD
100kΩ
K1
K2
D2
BAT54A
A
100nF
100nF
Q3
AO3400
IC1d
9
8
IC1: 74HC04
G
D
S
VDD
2x
5.1kΩ
Q7
AO3401
Q8
AO3401
IC1: 74HC04
IC1b
3
4
7
Q2
AO3400
S2b
A2
A1
A2
A1
S2a
SK1 40-PIN ZIF
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
MODE SWITCH
S1a
S1b
S1c
S1d
MCLR
PGD
PGC
22Ω
22Ω
VDD
VDD
VDD
Q11
BSS84
IC1c
5
6
100nF
Q10
2N7002K
PICkit
MCLR
VDD
GND
PGD
PGC
CON1
VDD
Q6
AO3401
5.1kΩ
100nF
Q4
AO3400
IC1: 74HC04
IC1e
10
11
IC1: 74HC04
IC1a
2
1
Q1
AO3400
LEDS 1–4
K
A
LED5
CATHODE DOT
BAV99
1
2
3
BAT54A
K1
K2
AO3400, AO3401, BSS84
2N7002
MCP1700
GND
IN
OUT
SC ©2023

MICRO PROGRAMMING ADAPTOR

Fig.2: routing of the MCLR, PGC and PGD signals from serial programmer header CON1 to ZIF socket SK1 is straightforward, via 4P4T slide switch S1 and DPDT slide switch S2. Connecting GND, VDD and the 47uF capacitor to the appropriate pins of SK1 is a bit more complicated. Switch pole S1d and hex inverter IC1 plus some diode logic control Mosfets Q1-Q11 to apply the correct voltages to the right pins. The VDD indicator circuit is at lower right.

P-channel (VDD switching) and N-channel (GND switching) Mosfet pairs. That is so they do not affect any SK1 pins when those Mosfets are off.

Pins 39 & 40

These are the only two pins that need to be switched between programming (PGD/PGC) and power pins. They are only used as power pins in mode D, for the PIC24/dsPIC/PIC-32MX series of chips, where they are the AVDD and AVSS pins. These pins draw almost no current during programming and a maximum of a few milliamps if the chip is running code that uses the ADC peripheral.

Mosfets have capacitance when off; the AO3400 and AO3401 Mosfets we're using to switch power to the other pins have rated output (drain) capacitances of 75pF (15V/1MHz) and 115pF (115pF/1MHz) respectively. The figures at 0-5V would be even higher and could easily be high enough to interfere with programming.

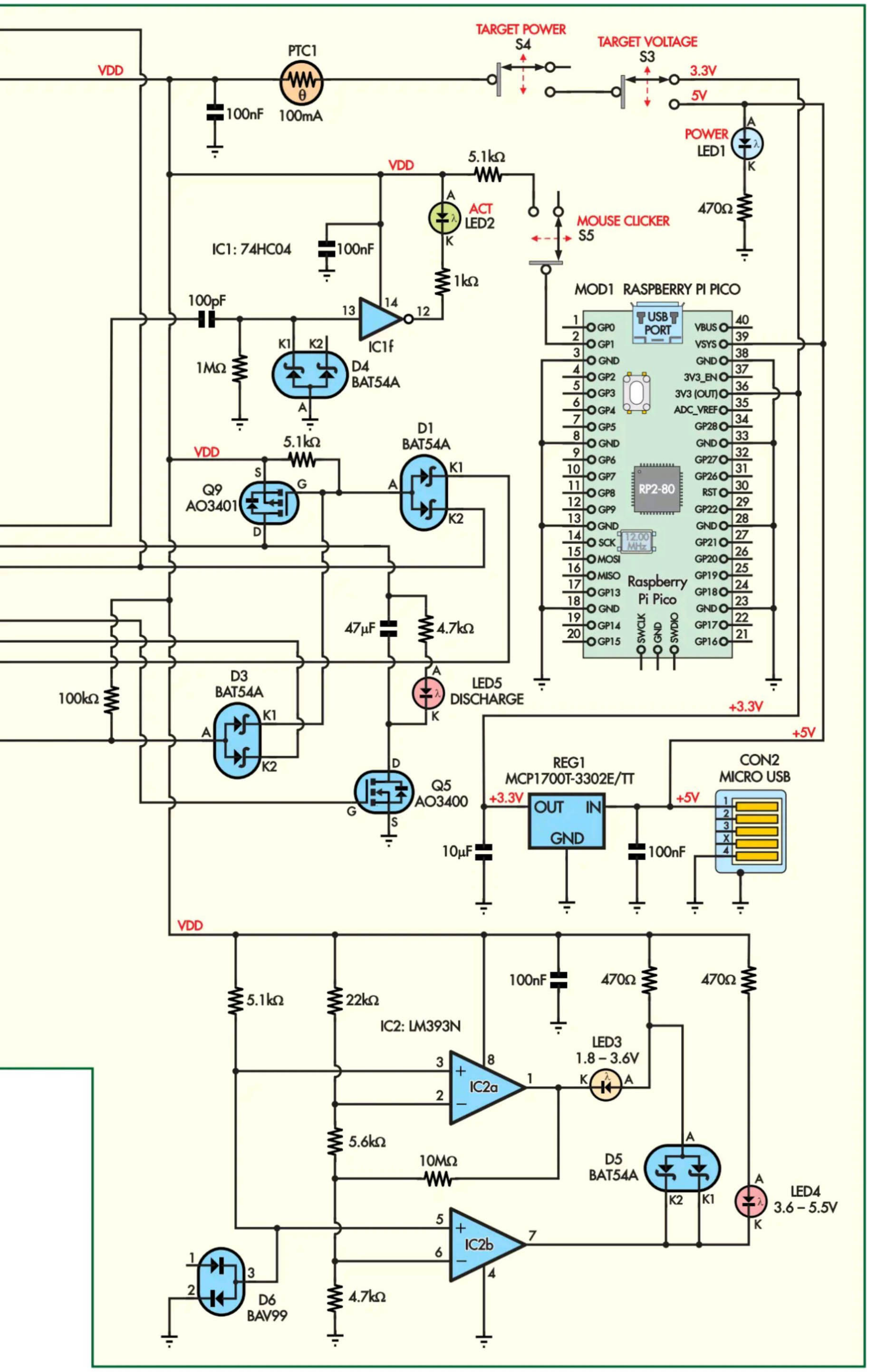
Therefore, we are using much smaller Mosfets to switch power to these pins. Q10 (2N7002K) is an N-channel Mosfet with an output capacitance of 13pF at 25V/1MHz, while Q11 (BSS84) is a P-channel Mosfet with an output capacitance of 10pF under the same conditions.

That's a lot better, but it still could possibly interfere with programming, so 22Ω isolating resistors have been added to reduce the effect on programming signals at those pins when the Mosfets are off. That value was chosen to balance minimising the voltage difference between AVDD/AVSS and VDD/VSS while also providing reasonable isolation.

Pin 32 (VCAP)

The VCAP pin needs to be connected via a capacitor to ground in mode D. That's achieved simply by permanently connecting a 47µF capacitor to that pin but switching its other end to ground via N-channel Mosfet Q5. This Mosfet is only on in mode D. When off, the Mosfet's ~100pF output capacitance is in series with the 47µF capacitor, making it effectively a 100pF capacitor.

LED5 and its 4.7kΩ series resistor across the VCAP capacitor are there to discharge it should it become charged


VDD
PTC1
100mA
100nF
TARGET POWER
S4
TARGET VOLTAGE
S3
3.3V
5V
POWER
LED1
A
K
470Ω
VDD
5.1kΩ
ACT
LED2
MOUSE CLICKER
S5
IC1: 74HC04
100nF
1kΩ
100pF
13
14
12
IC1f
1MΩ
K1
K2
D4
BAT54A
A
MOD1 RASPBERRY PI PICO
USB PORT
GP0
GP1
GND
GP2
GP3
GP4
GP5
GND
GP6
GP7
GP8
GP9
GND
SCK
MOSI
MISO
GP13
GND
GP14
GP15
VBUS
VSYS
GND
3V3_EN
3V3 (OUT)
ADC_VREF
GP28
GND
GP27
GP26
RST
GP22
GND
GP21
GP20
GP19
GP18
GND
GP17
GP16
RP2-80
12.00 MHz
Raspberry Pi Pico
SWCLK
GND
SWDIO
VDD
5.1kΩ
D1
BAT54A
Q9
AO3401
S
G
D
47μF
4.7kΩ
LED5
DISCHARGE
100kΩ
D3
BAT54A
+3.3V
+5V
REG1
MCP1700T-3302E/TT
OUT
IN
GND
CON2
MICRO USB
Q5
AO3400
10μF
100nF
VDD
5.1kΩ
22kΩ
100nF
470Ω
470Ω
IC2: LM393N
LED3
1.8 – 3.6V
IC2a
IC2b
5.6kΩ
10MΩ
D5
BAT54A
LED4
3.6 – 5.5V
D6
BAV99
4.7kΩ

above about 1.8V. That's because pin 32 is also VDD in modes B and C, so if you have the power on and switch between modes C and D, there will be a brief overlap between the application of VDD to pin 32 and Q5 switching on, so the 47μF capacitor will charge to VDD.

This capacitor could hold that VDD voltage for a long time. When a target device is later inserted in SK1 that uses pin 32 as VCAP, that capacitor's charge would be dumped into that pin, which is only intended to handle up to about 1.8V.

To prevent that, as soon as the Adaptor is switched into mode D and Q9 switches off, the 47μF capacitor rapidly discharges to around 1.8V via LED5 (in around one second). LED5 will briefly light to let you know this is happening. Once it extinguishes, it is safe to insert a chip that's programmed in mode D.

Target power switching

The target device (PIC) can be powered from a PICkit plugged into CON1. However, there are many cases where it's more convenient to supply power externally, and if you're using a Snap programmer, it can't deliver power. Therefore, switch S4 applies power to the target device via PTC1, which goes high-resistance if the target draws too much current.

That's only likely if you have the wrong chip in the socket, the wrong mode selected, or the target is orientated incorrectly. In these cases, PTC1 might prevent it from being damaged.

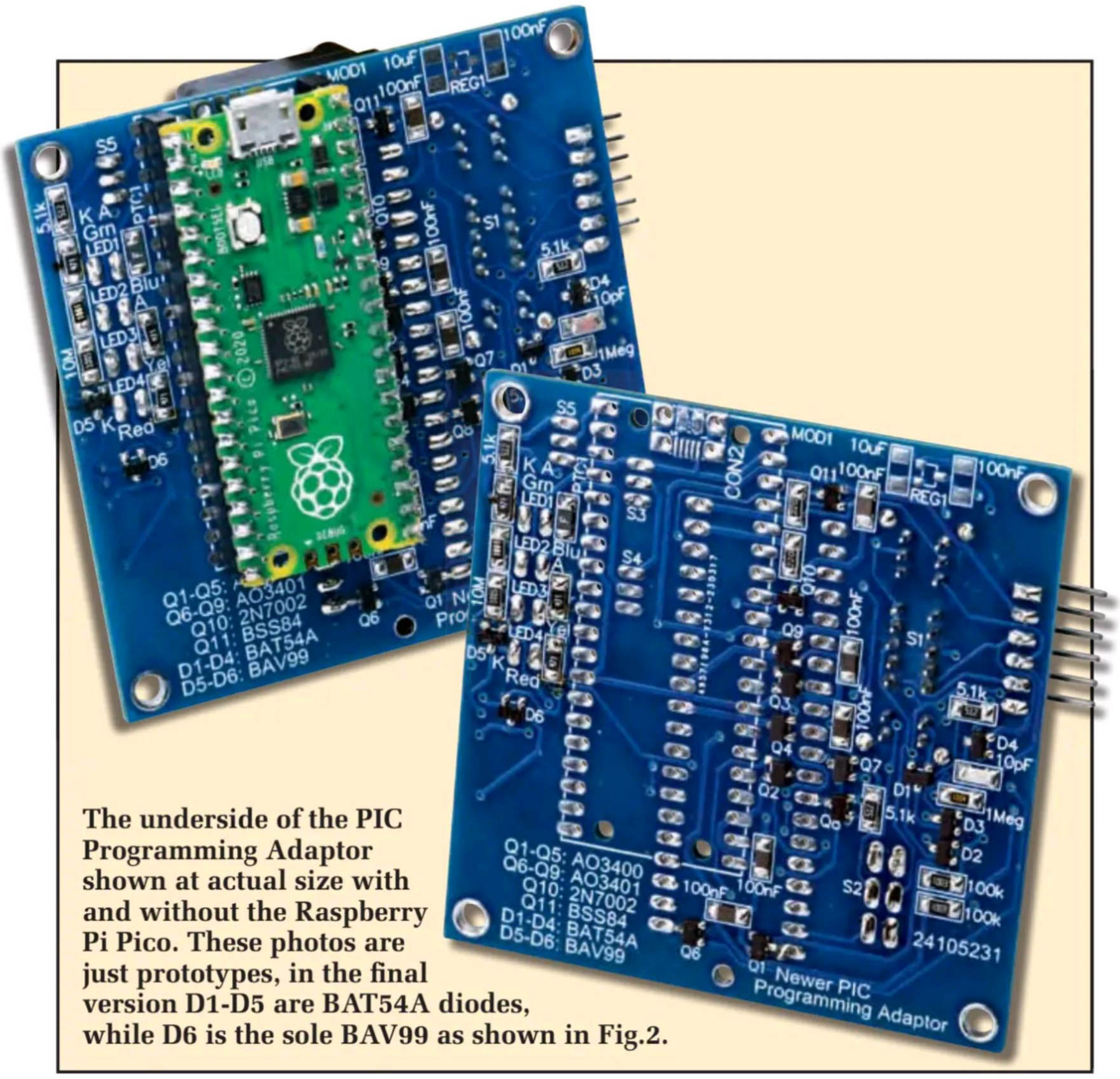
PIC16LF, PIC24, dsPIC and PIC32MX devices all need a 3.3V supply, while PIC16F devices can usually run from 3.3V or 5V. Some older chips require 5V for programming, although most modern PICs can be programmed at 3.3V. Therefore, switch S3 can generally be left at its 3.3V setting, although you can supply 5V to the target if you wish.

Both the 3.3V and 5V sources come from a Raspberry Pi Pico, MOD1, which would typically be powered from a USB charger or a computer (presumably, the same one doing the programming). LED1 indicates when power is available from the Pico.

The Pico also provides the mouse clicker function – more on that later. If you don't need that function, it's still a reasonable way to provide power to the board, but you can leave it off and fit USB connector CON2, regulator REG1 and its input and output capacitors. REG1 is a low-dropout regulator providing a 3.3V rail from the USB 5V supply.

Programming indication

LED2 lights when there is an AC waveform at the PGD pin of CON1. This signal is coupled via a 100pF capacitor and biased to 0V with a 1MΩ resistor to minimise any effect on the actual programming. Whenever PGD goes low, the 100pF capacitor discharges through diode D4. When it goes high, input pin 13 of inverter



The underside of the PIC Programming Adaptor shown at actual size with and without the Raspberry Pi Pico. These photos are just prototypes, in the final version D1-D5 are BAT54A diodes, while D6 is the sole BAV99 as shown in Fig.2.

IC1f goes high, so its output goes low, lighting LED2, which draws around 1-2mA.

Because PGD toggles very fast, LED2 should appear to light solid when PGD is toggling, albeit at reduced brightness.

You might notice that the prototype was built with LED1 as green and LED2 as blue, while everything else shows it the other way around. That's because a blue LED typically has a forward voltage of at least 3V, so it seemed to make more sense in hindsight for LED1 to be blue, as it's powered from 5V, while LED2 could be powered from 3.3V or less.

In practice, the blue LED2 on our prototype lights up just fine with VDD at 3.3V, and we don't intend to program chips at voltages below that. Ultimately, it's up to you how you arrange the colours.

LED3 and LED4 are provided so that you know when power is applied to the target and that it is in the expected voltage range. Dual comparator IC2 provides this function. A ~0.6V reference voltage is developed at pins 3 and 5 of IC2 by half of diode D6, which is forward-biased by a 5.1kΩ resistor from the VDD rail.

A 22kΩ/5.6kΩ/4.7kΩ divider across the VDD rail applies two fractional voltages to pins 2 and 6 of the same chip. These are roughly 16% and 33% of the VDD voltage. Therefore, the output of comparator IC2a goes low when VDD exceeds 0.6V ÷ 33% = 1.8V, and the output of IC2b goes low when it exceeds 0.6V ÷ 16% = 3.75V.

Note that the ~0.6V reference from D6 varies slightly with VDD; hence, the percentages and voltages above are not exact. LED3 comes on with a supply voltage just below 1.8V (dimly, since that's barely above the LED's forward voltage), while LED4 comes on a little over 3.8V, which is higher than the 3.6V indicated. Still, in most cases, VDD will either be below 3.6V or above 4.5V.

If VDD > 3.8V and output pin 7 of IC2b is low, LED4 is forward-biased and lights with around 6mA ([5V – 2V] ÷ 470Ω). At the same time, diode D5 is forward-biased and pulls the anode of LED3 low, so LED3 cannot also light.

If VDD < 3.8V and LED4 is off, LED3 will light if output pin 1 of IC2a is low. That is the case when VDD is between 1.75V and 3.8V. The 470Ω resistor limits its current to a few milliamps.

Note that LED4 will not extinguish if VDD is above 5.5V; however, the USB supply should never be high enough to allow that, nor should the VDD output of a PICkit. Also note that if you change the colour of LED3 to anything other than red, yellow or amber, it might not light up for lower VDD voltages (1.8-2.2V and possibly higher, depending on its colour).

Mouser clicker

The mouse clicker using the Raspberry Pi Pico was previously described in a "Mouser Clicker" project, reproduced in a panel at the end of this article. When connected to the computer, the Pico appears as a mouse and triggers a click whenever its GP1 pin (pin 2) is pulled externally high. This will be the case when VDD is switched on as long as slide switch S5 is in the correct position.

You position the mouse cursor over the "Program" button on your software, then, with the programming rig already set up, you put the chip in the ZIF socket and switch target power on. The Pico will click the Program button, and the chip will be programmed. You can then switch the target power off, remove the chip and insert another one, ready for programming.

The whole process can take just a few seconds per chip.

The Pico will do nothing with S5 off as there is nothing to pull its pin 2 high; an internal pull-down current keeps that pin low.

Construction

The Programming Adaptor is built on a 65.5 × 66mm PCB coded 24105231. We had ours made with a blue solder mask because we thought it'd look nice, especially as many people would use it as a bare board. There are components on both sides; Figs.3 & 4 show where they are mounted.

The top side mostly has the connectors and switches, with almost all the Mosfets on the underside. The Pico mounts on the underside too. We have purposefully avoided putting any components under it, but there are solder joins for SK1, S3 and S4 under it, so it needs to be mounted on headers for spacing. We'll get to that a bit later.

The first parts to fit are the SMDs, as they are pretty flat. Because most of them are on the underside, it's best to start there. All SMD components on the underside are either 3.2 × 1.6mm (imperial 1206) passives (including the PTC) or three-pin SOT-23 package Mosfets or diodes.

Start with the SOT-23 package devices, ensuring you don't mix up the six or seven types. Their orientations should be evident but watch that you don't accidentally try to solder them upside-down, with their leads sticking up in the air, 'dead bug' style.

You don't need to fit REG1 if you will use the Pico (which we recommend).

For parts like Q2, where its central pin is very close to a through-hole pad, avoid getting solder on that nearby pad. If you do, and it goes into the hole, you might have difficulty soldering the ZIF socket later. If you get some in there, clean it up as best you can with flux paste and some solder wick or a solder sucker.

For each 3-pin device, tack one lead, check the positioning, then solder the other two. Adding a tiny bit of flux paste on the three pads from a syringe before locating the part will make the solder flow much more easily. Verify that all three solder joints are shiny and have adhered to both the pin and the pad; if they are not shiny, add a touch of flux paste to the joint and touch your iron to it to reflow it.

With all the SOT-23 devices in place, move on to the resistors, capacitors and PTC thermistor that mount on the underside, none of which are polarised. The two capacitors right next to REG1 do not need to be fitted if you are not using REG1.

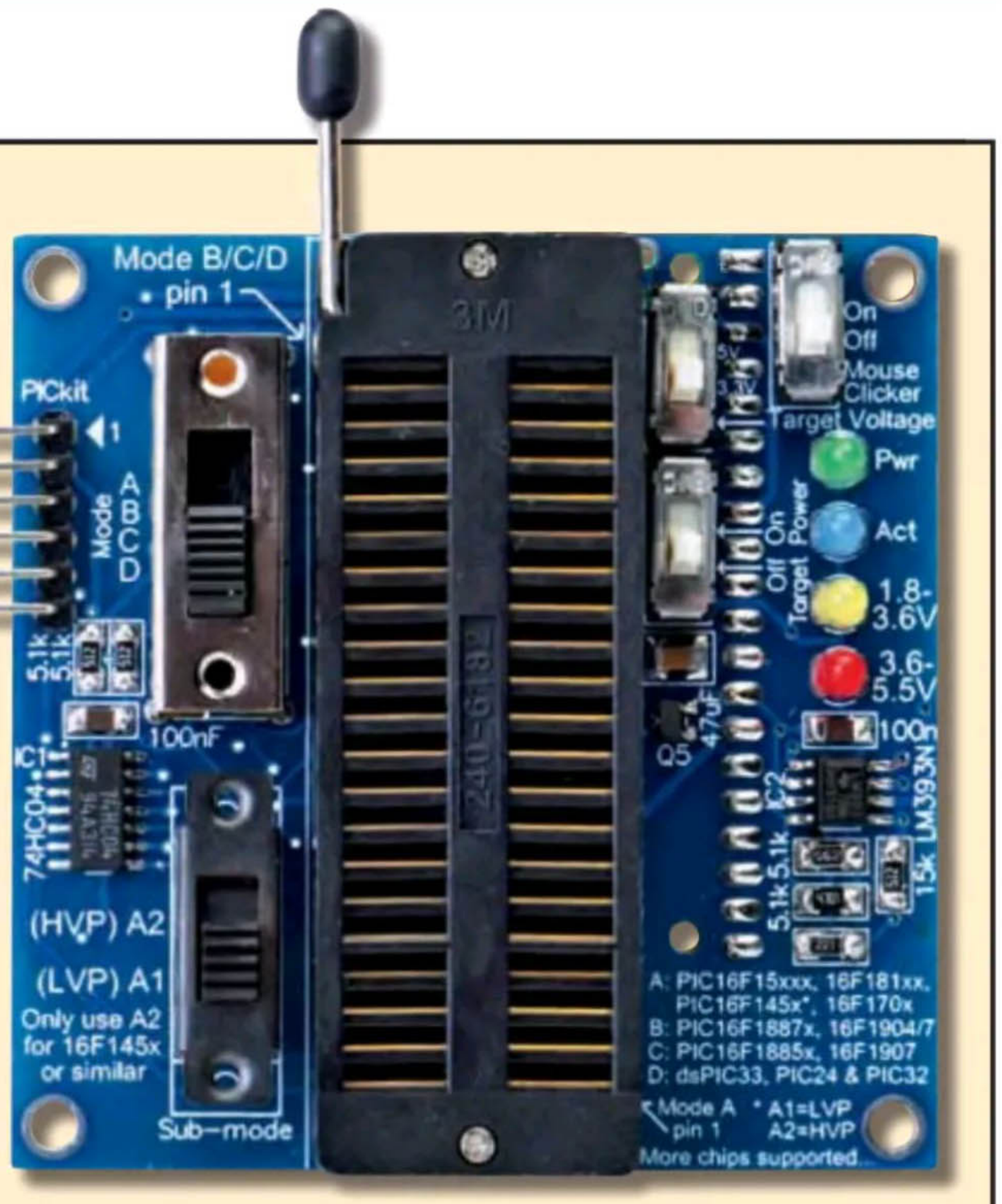
The resistors will be printed with codes like 102 or 1001 for 1kΩ, 1005 or 106 for 10MΩ etc. Use a magnifier to read them, if necessary. The capacitors will not be labelled, so take them out of their packages one lot at a time and solder them in place so you don't get them mixed up.

Now is a good time to clean flux residue off the board; we really like Chemtools' Kleanium Deflux-It G2 Flux Remover, but you can use some alcohol or acetone instead if that's all you have on hand. Inspect the solder joints under magnification to verify they're all good.

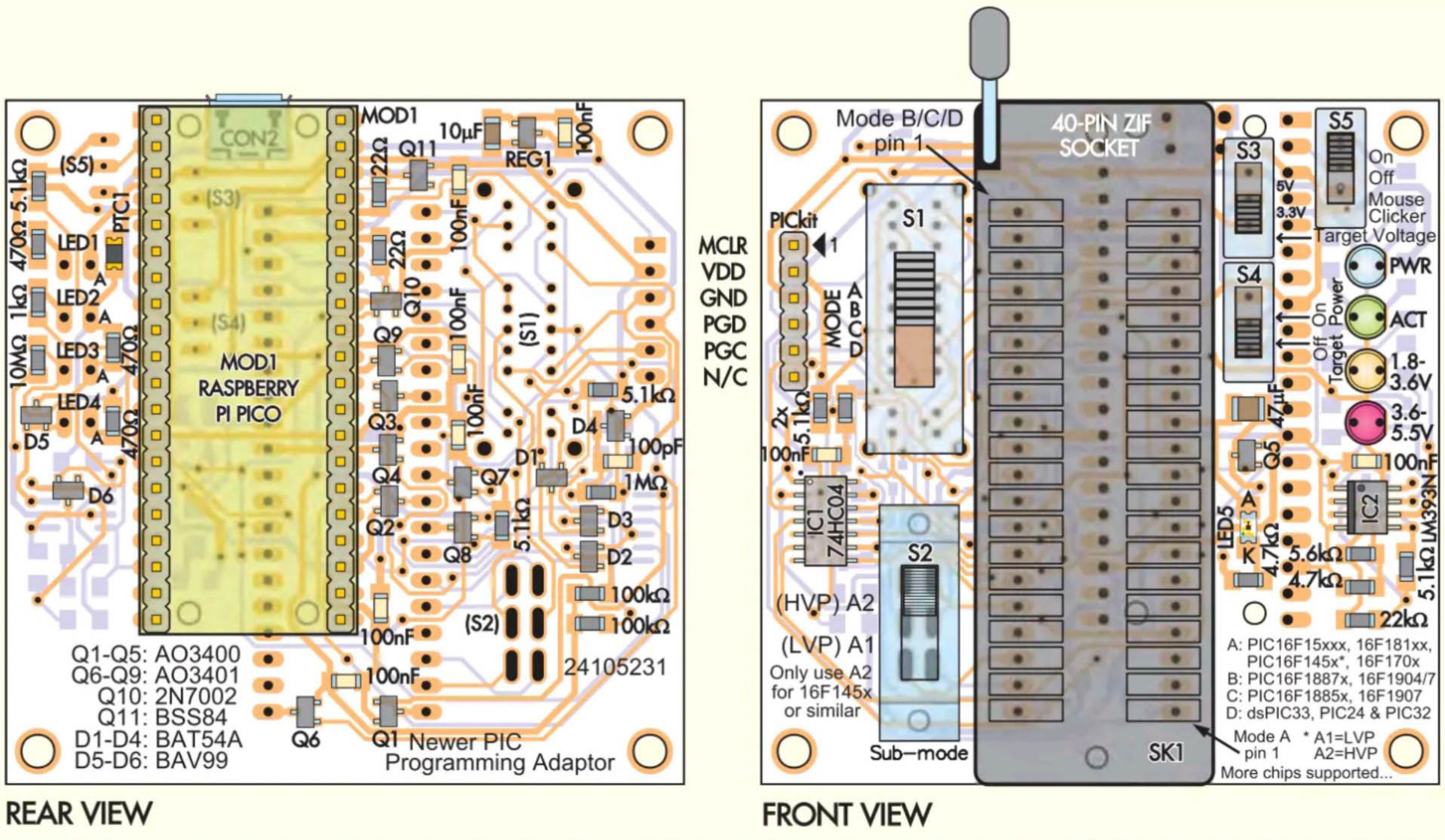
The only remaining components to fit on the underside are either the Pico or USB socket, depending on which you're using, but leave them off for now and flip the board over. Solder the two SMD ICs, ensuring their pin 1 indicators (dots, chamfered edges etc) are at upper left, as shown in Fig.3.

These are in SOIC packages with relatively widely spaced pins. After tacking one and checking the placement and orientation, you can either solder the remainder individually or apply some flux paste along the edge and drag solder the pins. Then mount Q5 (the only SOT-23 package device on the top side), then the resistors and capacitors, using the same technique as before. None of the passives are polarised.

Note that the 47µF capacitor may be the same size as the others or a little larger. Larger pads are provided that suit a range of components from 2.0 × 1.2mm (imperial 0805) up to 3.2 × 2.8mm (imperial 1210).


Mode B/C/D
• pin 1
PICkit
Mode
A
B
C
D
5.1k
100nF
IC1
74HC04
(HVP) A2
(LVP) A1
Only use A2
for 16F145x
or similar
Sub-mode
3M
On
Off
Mouse
Clicker
Target Voltage
Off On
Target Power
Pwr
Act
1.8-
3.6V
3.6-
5.5V
47uF
Q5
100n
IC2
LM393N
5.1k 5.1k
15k
A: PIC16F15xxx, 16F181xx,
PIC16F145x*, 16F170x
B: PIC16F1887x, 16F1904/7
C: PIC16F1885x, 16F1907
D: dsPIC33, PIC24 & PIC32
Mode A * A1=LVP
pin 1 A2=HVP
More chips supported...

We designed this as a compact board so it doesn't take up much space on your workbench, even with a PICkit or similar hanging off the side. That requires the controls to be closely spaced together, but we find them all to be accessible enough during use. This version of the PCB lacks SMD LED5, which was added later.


(S5)
5.1kΩ
PTC1
LED1
470Ω
1kΩ
LED2
LED3
10MΩ
470Ω
LED4
470Ω
D5
D6
CON2
(S3)
(S4)
MOD1
RASPBERRY
PI PICO
MOD1
22Ω
Q11
10µF
REG1
100nF
22Ω
Q10
Q9
100nF
(S1)
Q3
Q4
Q2
Q7
Q8
100nF
5.1kΩ
D4
100pF
D1
1MΩ
5.1kΩ
D3
D2
100kΩ
100kΩ
(S2)
100nF
100nF
24105231
Q1-Q5: AO3400
Q6-Q9: AO3401
Q10: 2N7002
Q11: BSS84
D1-D4: BAT54A
D5-D6: BAV99
Q6
Q1
Newer PIC
Programming Adaptor
REAR VIEW
MCLR
VDD
GND
PGD
PGC
N/C
Mode B/C/D
• pin 1
40-PIN ZIF
SOCKET
PICkit
1
S1
MODE
A
B
C
D
2x
5.1kΩ
100nF
IC1
74HC04
S2
(HVP) A2
(LVP) A1
Only use A2
for 16F145x
or similar
Sub-mode
SK1
S3
5V
3.3V
S5
On
Off
Mouse
Clicker
Target Voltage
S4
Off On
Target Power
PWR
ACT
1.8-
3.6V
3.6-
5.5V
47µF
Q5
100nF
IC2
LM393N
LED5
A
K
4.7kΩ
5.6kΩ
4.7kΩ
5.1kΩ
22kΩ
A: PIC16F15xxx, 16F181xx,
PIC16F145x*, 16F170x
B: PIC16F1887x, 16F1904/7
C: PIC16F1885x, 16F1907
D: dsPIC33, PIC24 & PIC32
Mode A * A1=LVP
pin 1 A2=HVP
More chips supported...
FRONT VIEW

Figs.3 & 4: fit the components on the relatively compact PCB as shown here. We recommend doing it in two stages, with the first stage mostly involving fitting the SMDs, starting on the underside, plus a few of the through-hole parts. Watch the orientations of the ICs and LEDs.

With all the SMDs in place, clean any flux residue off the top of the board, as you did for the underside, and inspect the solder joints.

Next, install the five LEDs. The four 3mm through-hole types are all orientated the same way, with the shorter (cathode) leads and flat lens edges towards the nearest edge of the PCB. We pushed them down flat onto the PCB before soldering the leads to keep them neat, but you could stand them off a little if you want to.

The SMD LED, LED5, is soldered similarly to the resistors and capacitors. It should have a small green dot or perhaps a T on the underside indicating the cathode, which faces towards the bottom edge of the board. If you aren't sure, set a DMM on diode test mode and probe the two ends of the LED. When it lights up, you have the red probe on the anode and black on the cathode.

The three remaining components to solder at this stage are switches S1 and S2 and header CON1. Before soldering the pins, ensure the switches are fully flat on the PCB. As S1 has many fairly small pins, it's a good idea to dab a little flux paste on each before soldering them to ensure they flow properly. Any bad joints here will cause problems later.

Step 1: check continuity

Mode A1
- *CON1 pin 1 to SK1 pin 24*
- *CON1 pin 4 to SK1 pin 19*
- *CON1 pin 5 to SK1 pin 18*

Mode A2
- *CON1 pin 1 to SK1 pin 24*
- *CON1 pin 4 to SK1 pin 16*
- *CON1 pin 5 to SK1 pin 15*

Mode B
- *CON1 pin 1 to SK1 pin 1*
- *CON1 pin 4 to SK1 pin 40*
- *CON1 pin 5 to SK1 pin 39*

Mode C
- *CON1 pin 1 to SK1 pin 1*
- *CON1 pin 4 to SK1 pin 40*
- *CON1 pin 5 to SK1 pin 39*

Mode D
- *CON1 pin 1 to SK1 pin 1*
- *CON1 pin 4 to SK1 pin 4*
- *CON1 pin 5 to SK1 pin 5*

Step 2: check voltages

Mode A1 / A2
- *SK1 pins 21 (red) & 20 (black)*

Mode B
- *SK1 pins 11 (red) & 12 (black)*
- *SK1 pins 32 (red) & 31 (black)*

Mode C
- *SK1 pins 32 (red) & 8 (black)*
- *SK1 pins 32 (red) & 31 (black)*

Mode D
- *SK1 pins 40 (red) & 39 (black)*
- *SK1 pins 13 (red) & 8 (black)*
- *SK1 pins 13 (red) & 31 (black)*

S2's solder lugs go into generously-sized slots on the PCB. The solder should flow in and quickly join them to the PCB; if in doubt, add more.

We suggest using a right-angle header for CON1, with the pins sticking out over the edge of the PCB, to keep the serial programmer out of the way in use (see our photos). Still, you could use a vertical header if you want to.

Testing

We now have enough components mounted on the board that we can do most of the testing before fitting the ZIF socket or Pico. You can still fix problems after that, but it will be harder, so let's test it now. Fit four tapped spacers to the corners of the board using short machine screws so it will sit flat on your desk.

We used two male/female jumper wires to connect to pins 2 & 3 of CON1 for applying power to the board from a bench supply. We suggest you do similar. Be careful with the polarity; the middle pin (pin 3) is GND, while pin 2, closer to the top, is VDD. If possible, start at 0V and slowly wind it up while monitoring the current draw. It should not exceed 30mA; if it does, switch it off and check for faults.

Once VDD exceeds about 1.8V, you should see LED3 starting to light. It will be pretty dim, though. LED1 will remain off as we are feeding power directly into VDD and not the 5V rail. LEDs 2 & 4 should also stay off at this stage.

Wind up the voltage to about 3.8V, and you should find that LED3 switches off and LED4 switches on. Continue increasing VDD to 5.5V, at which point LED4 should be pretty bright and the circuit should be drawing around 20mA. That confirms that IC2 is functioning correctly.

If something different happens, check the soldering on IC2 and its surrounding components. Check that IC2 has been installed the right way around and that the surrounding component values and types are correct. Also check the orientations of the LEDs.

Assuming that's fine, wind the supply back to 3.3V. We are now ready to check all the routings for programming chips in the five different modes. To help you do this, we've added ZIF socket pin numbers to the top of the PCB since building the prototype.

While you could work out the connections based on Figs.1 & 2, to make things easier, here are all the connections you need to probe. We'll start with MCLR, PGD and PGC. Set a DMM to continuity test/buzzer mode (or low ohms if your meter doesn't have such a mode) and then check that all the pin pairs in the Step 1 box are connected in each mode, set using S1 & S2.

If any of these lack continuity or have a resistance reading above 1Ω, that suggests a bad solder joint on CON1, S1 or S2, so check those. They are the only components making those connections. The only other problem could be a faulty PCB, but that's very unlikely. Still, if you've ruled the other parts out, you will have to trace the tracks and check them.

Next, we check that GND and VDD are fed to the correct pins in each mode. Set your DMM to measure volts (eg, 20V range or similar) and then probe the pairs of pins in the Step 2 box in each mode. In each case, you should get a steady 3.3V (or whatever the exact voltage you are applying to the circuit is).

If any of those are wrong, look for soldering or component placement problems with IC1 and the components like Mosfets, diodes & resistors associated with the problematic pin(s).

Finally, measure the capacitance between pins 32 and 31 with it still set to mode D. You should get a reading close to 47uF. If you don't have a suitable meter, check the voltage between pins 32 and 31. It will likely be around 1.8V, slowly dropping as the capacitor discharges through your meter. If it's near 0, switch to mode C and back to mode D (LED5 should light briefly), then check again.

If you measure more than 2V between pins 32 and 31, something is wrong with the protection circuitry involving LED5, so check its orientation and soldering, and the soldering of its 4.7kΩ series resistor.

Finishing it

Remove the spacers from the corners of the board and solder switches

S3, S4 and S5 in place, making sure they are pushed all the way down and neatly aligned and vertical (solder one pin, check, then solder the rest). That leaves SK1 and the Pico (or USB socket CON2 if you aren't using the Pico).

If not using the Pico, solder CON2 now, checking that its small pins are correctly aligned with their pads before soldering the four through-hole mounting tabs. Then solder the signal pins, being careful not to bridge them (use flux paste and wick to fix it if you do) as they are very close together.

Mounting the Pico is a little tricky since one of its rows of pins is opposite the ZIF socket. The ZIF socket has only about half a millimetre of clearance between its plastic body and the top of the PCB, and we've used through-hole headers for simplicity. Luckily, it isn't all that hard to work with this arrangement.

Our solution is as follows, although we'll mention another possibility later.

We started by inserting two low-profile 20-pin female headers into the rows of Pico pins on the underside of the board. Then we inserted two 20-pin regular male headers with the short sides into those sockets and placed the Pico on top, with the longer pins going through its pads. The Pico's USB socket faces away from the main board (see the photos).

We then pushed the two sockets fully onto the PCB and made sure they were perpendicular to it before soldering all their pins. After that, we soldered the headers to the pads on top of the Pico. Note that you could solder the headers in the usual manner – with the short pins on the Pico side – but then the headers will not fully insert into the low-profile sockets.

A neater option would be to use low-profile headers on the Pico, allowing you to use slightly shorter (eg, 12mm) spacers as feet for the board.

The trick now is to use a pair of sharp sidecutters to snip all the header socket solder joints as close to the PCB as possible that will be under the ZIF socket. Don't cut the whole solder joint off but try to keep each one to a maximum of around 1mm above the top of the board.

You can then insert the ZIF socket into its pads (straightening its pins if necessary). It won't quite push down all the way, but all its pins should go through the PCB and stick out the other side by about 1mm, which is enough to solder them comfortably. You might want to put ~1mm shims under it at both ends so it's sitting evenly, although we evened it up by eye.

Optionally, add a little flux paste onto the ZIF socket pads before soldering all 40 pins. That will ensure the solder flows smoothly and wicks into the through-holes around the pins, giving a solid mechanical and electrical bond.

The other option we considered, which is a bit simpler, was first fitting SK1 pushed all the way down, then soldering headers to the Pico in the usual way. It is then possible to insert those headers into the PCB pads until they touch the underside of the ZIF socket, making sure it is parallel to the main PCB, then solder them from the side. However, that will make the Pico captive.

We purposely avoided putting any components under the Pico, so that is not unreasonable, but half the ZIF socket solder joints will be inaccessible. So you'll want to ensure they are all good before doing that.

Parts List – PIC Programming Adaptor

1 double-sided PCB coded 24105231, 65.5 × 66mm
1 6-pin header, straight or right-angle (recommended), 2.54mm pitch (CON1)
1 Raspberry Pi Pico (MOD1)
(**optional**; alternative power supply parts are listed below)
1 40-pin universal ZIF socket (SK1)
1 4P4T vertical PCB-mount slide switch (S1) **[SS-44D02-G10]**
1 DPDT sub-miniature vertical solder tag slide switch (S2)
[Jaycar SS0852, Altronics S2010]
3 SPDT micro vertical slide switches (S3-S5) **[Jaycar SS0834]**
4 M3-tapped 15mm hex spacers
(can be 12mm if low-profile headers are soldered to Pico)
4 M3 × 6mm panhead machine screws
2 20-pin low-profile female headers, 2.54mm pitch (for MOD1)
2 20-pin headers, 2.54mm pitch
(for MOD1; ideally low profile but regular headers will work)

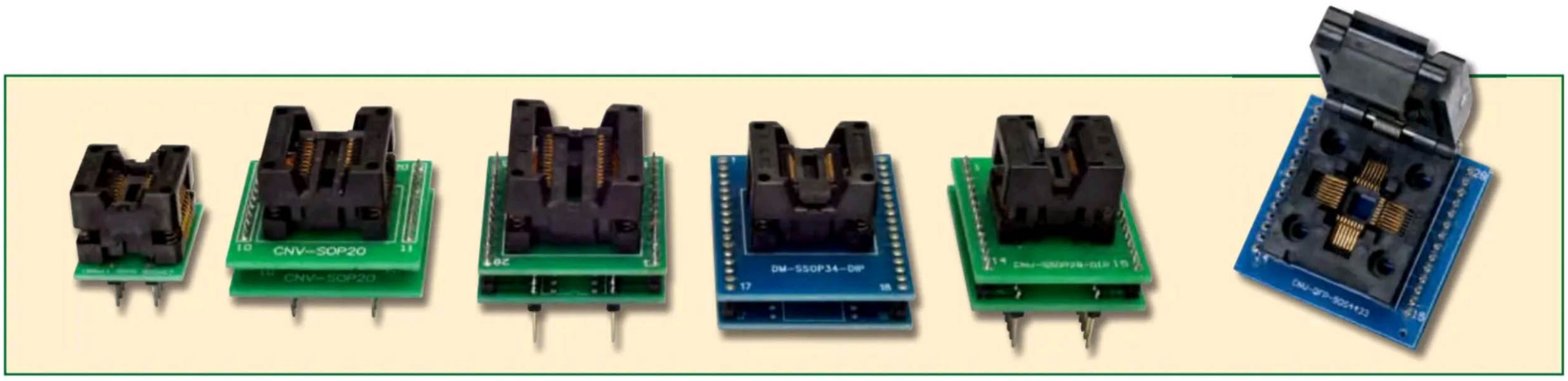
Semiconductors
1 74HC04 hex CMOS inverter, SOIC-14 (IC1)
1 LM393 dual single-supply comparator, SOIC-8 (IC2)
5 AO3400 logic-level, low $R_{DS(on)}$ N-channel Mosfets, SOT-23 (Q1-Q5)
4 AO3401 logic-level, low $R_{DS(on)}$ P-channel Mosfets, SOT-23 (Q6-Q9)
1 2N7002K logic-level N-channel Mosfet, SOT-23 (Q10)
1 BSS84 logic-level P-channel Mosfet, SOT-23 (Q11)
4 3mm LEDs with diffused lenses; blue, green, red & yellow (LED1-LED4)
1 SMD high-brightness red LED, M3216/1206/SMA package (LED5)
5 BAT54A dual common-anode schottky diodes, SOT-23 (D1-D5)
1 BAV99 dual series signal diode, SOT-23 (D6)
1 100mA PTC thermistor (PTC1) **[eg, 1206L050YR]**

Capacitors *(all SMD X7R ceramic, M1206 or M0805 size unless noted)*
1 47μF 6.3V X5R or X7R, M3226/1210, M3216/1206 or M2012/0805 size
7 100nF
1 100pF

Resistors *(all SMD 1%, M3216/1206 or M2012/0805 size unless noted)*
1 10MΩ 5%
1 1MΩ
2 100kΩ
1 22kΩ
1 5.6kΩ
6 5.1kΩ
2 4.7kΩ
1 1kΩ
3 470Ω
2 22Ω

Parts for optional USB power supply
1 SMD micro-USB socket (CON2)
1 MCP1700T-3302E/TT 3.3V low-dropout linear regulator, SOT-23 (REG1)
1 10μF 6.3V X5R or X7R ceramic capacitor, M3216 or M2012 size
1 100nF 50V X7R ceramic capacitor, M3216 or M2012 size

Optional SMD adaptor recommendations
Narrow SOIC (0.15"), 8-16 pins **[AliExpress; pemag.au/link/ablr]**
Wide SOIC (0.3"), 20-28 pins **[AliExpress; pemag.au/link/abls]**
MSOP-8 **[AliExpress; pemag.au/link/ablt]**
SSOP-28 **[AliExpress; pemag.au/link/ablu]**
TSSOP-28 **[AliExpress; pemag.au/link/ablv]**
(unsuitable for SSOP, despite what the description says!)



The PIC Programming Adaptor can be used with a variety of SMD-to-DIP adaptors, allowing you to program SMD chips. For example, the adaptors shown above plug directly into the 40-pin ZIF socket. The adaptor on the right is actually for an ATmega328; we'll have more on programming SMD chips in next month's issue.

Only pins 2, 36, 38 & 39 of the Pico need to be soldered. All the GNDs are connected on the board, but one (eg, pin 38) is sufficient. So you could solder just those pins, allowing you to desolder it later if necessary.

Finally, reattach the spacers to the corners of the board to act as feet.

Final testing

You can now plug the board into your computer via a USB cable and check that LED1 lights. Switch on S4, and either LED3 or LED4 should light, depending on the position of S3. Switching S3 should alternate between LED3 on/LED4 off and LED4 on/LED3 off.

You can now test program a chip. Switch it off, select the appropriate mode and put the chip in the ZIF socket. Plug your serial programmer into CON1 and ensure S3 is set to the appropriate voltage (3.3V is safe). Set S5 off, then switch on target power with S4. Check that your programming software can connect to, program and verify the chip.

If you are using the Pico, program it (if you haven't already) by downloading the firmware package (see the link at the end of the item opposite) and copying the .uf2 file onto the virtual drive that appears when the Pico is first plugged into your comluter.

With the Pico programmed, switch off the target power and set S5 on to test the mouse clicker. Put your computer's mouse over something that will let you know if it's clicked, then switch S4 on. Your computer should act like the mouse was clicked.

Using it

It's pretty straightforward, but we have a few hints. Firstly, you might want to stick a rubber foot to the underside of your serial programmer or place something about 12mm thick under it, so it doesn't try to pull the board over.

While you can change the mode with the target power on, doing that with it off is safer. Don't change the mode with the target power on if there's a chip in the ZIF socket. In general, it's best to fully set up the programming rig before inserting a device to program.

All the chips we tested can be programmed at 3.3V, so you can generally leave S3 on that setting. That way, you won't accidentally apply 5V to a chip with a maximum 3.6V rating. Some older chips that are compatible with this board need 5V for programming; if doing that, we suggest changing back to 3.3V immediately afterwards to be safe.

If you change to mode D with the power on, ensure LED5 is not illuminated before inserting a device in the ZIF socket. You might notice LED5 glowing very dimly with target powered enabled in mode D; that is normal.

If programming several chips using Microchip MPLAB IPE, after you've used the Connect button to let the programmer identify the first chip, hover the mouse cursor over the "Program" button, then switch on the target power. It should trigger programming almost immediately. When that finishes, switch off the target power, remove the chip, insert the next one, and switch the target power back on. Repeat as needed.

If you have a PICkit, you can let it power the target chips. In that case, you will need to Disconnect/Reconnect each time so that you aren't pulling a chip out of the ZIF socket while it's powered. When powering the target from the PICkit, leave S4 off.

SC6774: a complete kit is available from the SILICON CHIP online shop. It includes the Pi Pico, but does not include the optional USB power supply parts.

Programming SMD chips

You can also use this Adaptor to program compatible chips with up to 28 pins in packages like SOIC, MSOP, SSOP and TSSOP. To do that, you need the appropriate SMD-to-DIP adaptor (also known as "test sockets"). They are not overly expensive, but you may need a few different types. Some we recommend are in the parts list; here are more details:

1. A 28-pin TSSOP adaptor will let you program any TSSOP chip we have come across, from 8 pins to 28 pins, although the common pin counts for TSSOP chips are 14, 20, 24 or 28 pins.
2. Similarly, a 28-pin SSOP adaptor will let you program any SSOP chip. While TSSOP and SSOP are very similar, they are not the same width, so you can't program an SSOP chip in a TSSOP socket and probably can't do the reverse.
3. Some 8-pin PICs are available in the even smaller MSOP package. For those, you will need an MSOP-specific socket.
4. SOIC/SOP chips come with 8 to 28 pins and, unfortunately, in different widths. Most chips below 16 pins are 0.15" (3.8mm) wide, while most chips from 20 to 28 pins are 0.3" (7.6mm) wide. 20-pin chips can come in either width. The sockets in the parts list suit these two widths, but be aware that 0.2" (5.1mm) wide SOIC/SOP chips also exist.

Coming up

Programming other SMD chips out of circuit, like SOT-23-5/6, TQFP-32/44/48/64/100 and others is possible, but it is less commonly required than the DIP and SOIC chips this Adaptor can handle. Still, we need to do it as we sell those chips programmed, and some readers may want to do that as well.

We have designed suitable rigs, and they are not easy to find commercially (or at reasonable prices). So we will have an article next month explaining how to program various types of micros (PICs, AVRs and others) in those packages. PE

Automatic mouse clicker

This ‘circuit idea’ was originally presented in the “Circuit Notebook” section of Silicon Chip magazine. We are reproducing it here to aid in understanding how the PIC Programming Adaptor sends ‘mouse click’ events to the host computer when it detects that the target microcontroller power supply becomes active.

When programming lots of microcontrollers, we go through the same process many times. We insert the chip in the socket, apply power, switch to the computer, click the Program button, verify it was successful, then go back to the programming board, switch off the power and remove the chip.

We thought it’d save a lot of time if we didn’t have to switch between the programming board and the computer; ideally, the computer would click the ‘program’ button for us as soon as power was supplied to the chip. This very simple circuit can do that. It takes advantage of the Raspberry Pi Pico’s ability to emulate a mouse.

It isn’t just for programming micros; any time you need to click a button on a computer in response to an external stimulus, this circuit could do it.

We used the Arduino IDE to produce a program for the Pico that ‘clicks’ the left mouse button when triggered. The trigger is simply an I/O pin configured as an input with an internal pull-up or pull-down. The click is triggered when the pin is pulled low or high (depending on the configuration) and stays that way for 300ms. The Pico waits for the state to reset before getting ready to trigger again.

In our case, we use the fact that power is switched to the chip to be programmed as the trigger. The 300ms delay also ensures that the micro’s power stabilises before starting the programming process.

The resistor circuit is sufficient if the computer powers the programming rig. You may not need to connect pin 3 if the Pi Pico and programmer are powered from the same computer, as the grounds will be common. The resistor ensures that a voltage mismatch does not cause damage.

In this case, use the “POWER_CLICK_2_RESISTOR.uf2” firmware file. The GP1 pin (pin 2) is set as an input with an internal pull-down. The positive and negative wires are connected to the target chip’s power pins for sensing. The Pico’s USB socket is connected via a USB lead to the computer that needs to be ‘clicked’. This method activates when around 1.5-2V is present on the positive wire.

We also tested a version using a 4N25 opto-coupler for more robust isolation. Here, we’ve configured GP1 as an input with an internal pull-up. When sufficient current flows through the 4N25’s LED via the 1kΩ current-limiting resistor, its output transistor turns on, pulling GP1 low. This arrangement triggers at similar voltage levels and should have no trouble dealing with inputs up to 15V.

This circuit requires the “POWER_CLICK_2_OPTO.uf2” firmware file.

We don’t recommend using any of these circuits for anything above 15V, and certainly not with mains power.

If you don’t need power sensing and just want to trigger a mouse click with a pushbutton or similar switch input, the third switch circuit will also work with the “POWER_CLICK_2_OPTO.uf2” firmware. In this case, the pushbutton pulls the GP1 pin to ground, similarly to the opto-coupler.

We’ve included the Arduino code with our downloads for this design. If you are familiar with the Arduino IDE, you can use it to modify and upload the code to the Pico.

If you don’t have the IDE or want to use the firmware as is, then hold the BOOTSEL button on the Pico while plugging it into the computer. A virtual flash drive (named ‘RPI-RP2’) should appear, and you can upload the firmware by simply copying the appropriate UF2 file to it.

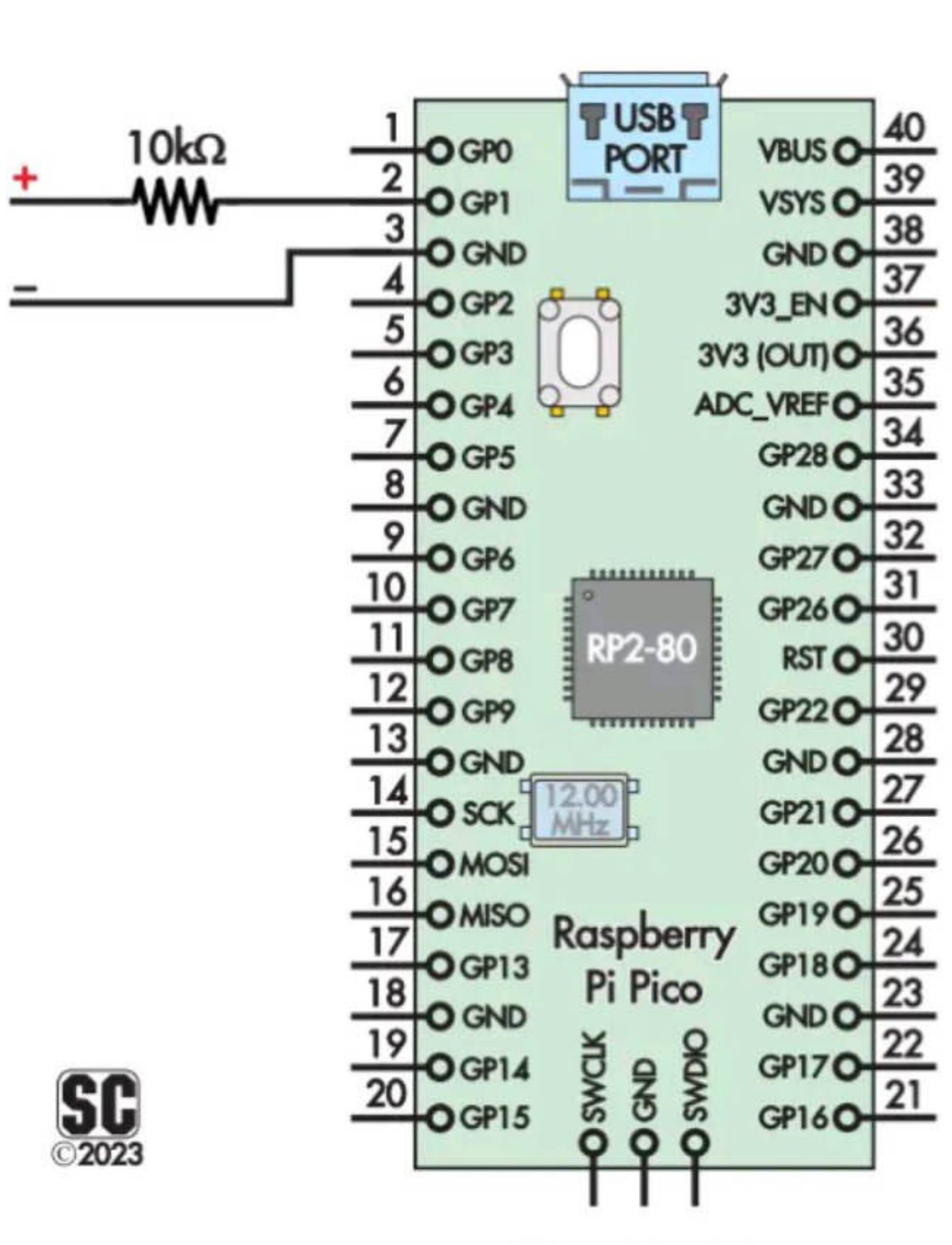
If you are using the OPTO version, you can test it by shorting pins 2 and 3 (GP1 and GND) on the Pico, remembering to account for the delay. This should have the same effect as clicking your mouse.

Besides the programming rig mentioned above, another possible use for this circuit is a 21st-century update on the Map Reader from Silicon Chip, March 1989 (**siliconchip.au/Article/7516**). It used a cheap pocket calculator to count pulses from a photo-interrupter attached to a wheel to measure distances on a map.

With our Clicker circuit and the Calculator application in Windows, we could get the same effect by entering “1+” in the calculator and then positioning the mouse pointer over the “=” button. Each click then increments the count.

You can download the firmware for the automatic mouse clicker from **https://pemag.au/Shop/6/116**

Tim Blythman, Silicon Chip.


+
10kΩ
–
USB PORT
RP2-80
12.00 MHz
Raspberry Pi Pico
GP0 GP1 GND GP2 GP3 GP4 GP5 GND GP6 GP7 GP8 GP9 GND SCK MOSI MISO GP13 GND GP14 GP15
VBUS VSYS GND 3V3_EN 3V3 (OUT) ADC_VREF GP28 GND GP27 GP26 RST GP22 GND GP21 GP20 GP19 GP18 GND GP17 GP16
SWCLK GND SWDIO
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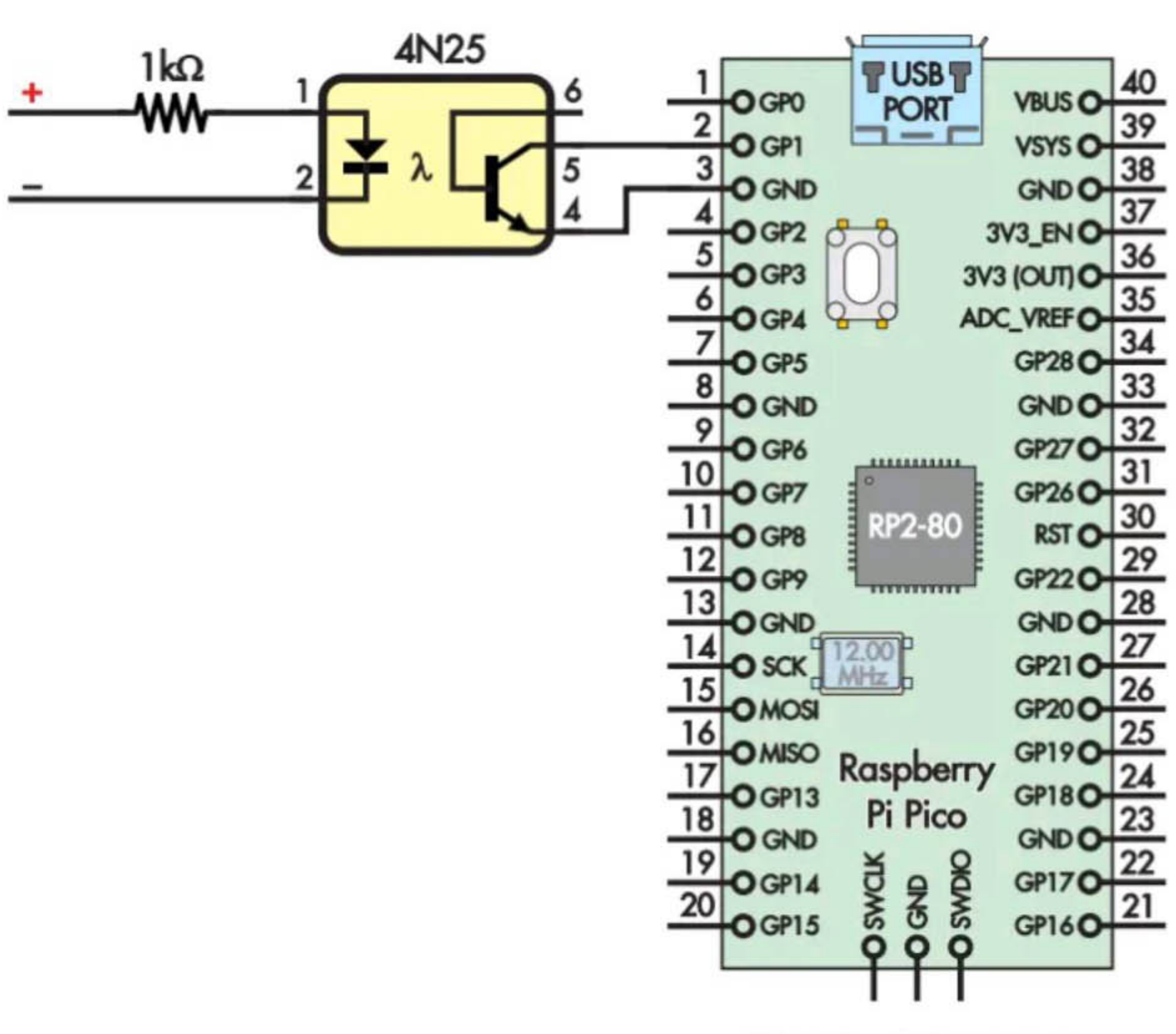
RESISTOR


+
1kΩ
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USB PORT
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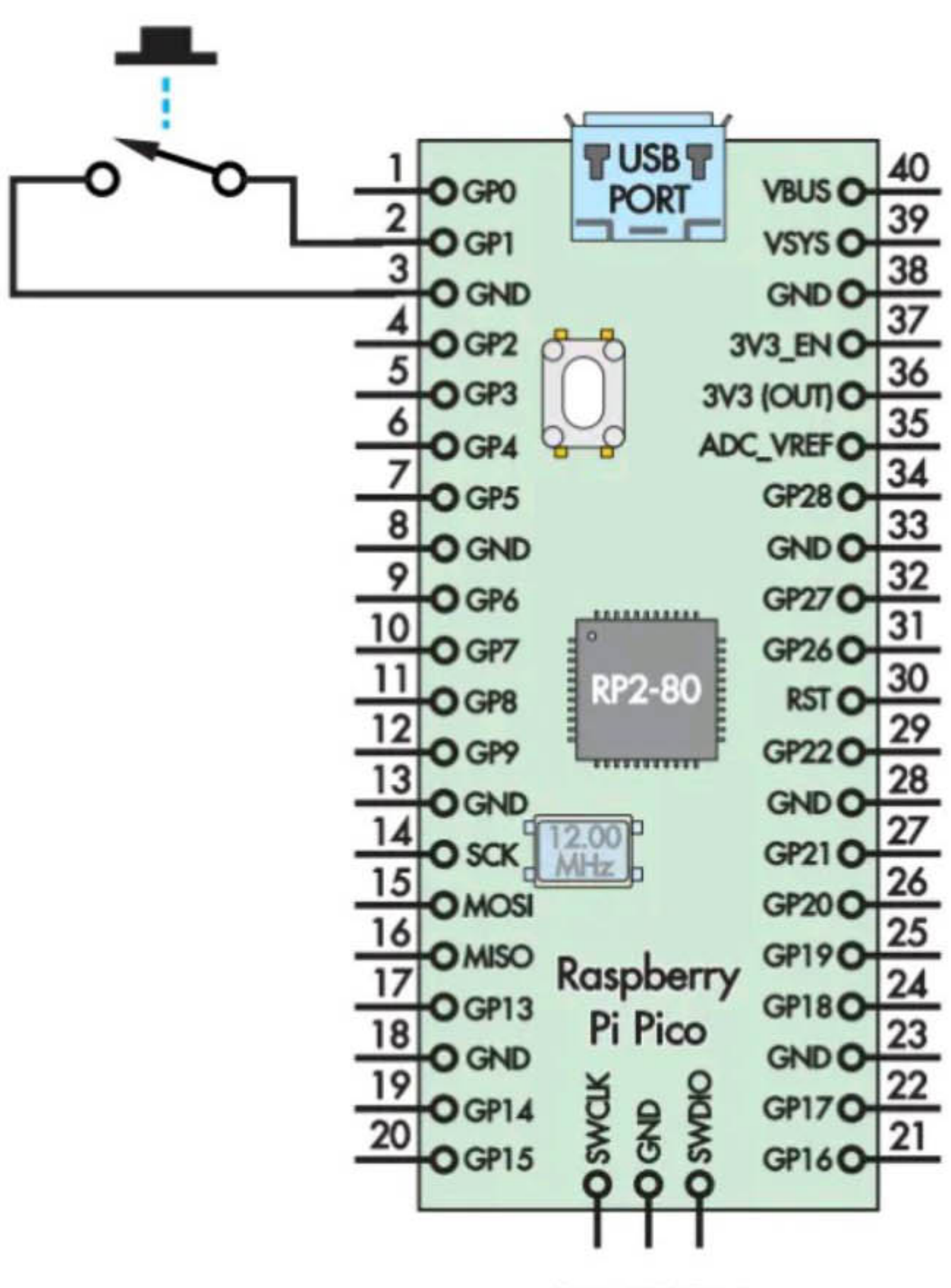
Raspberry Pi Pico
GP0 GP1 GND GP2 GP3 GP4 GP5 GND GP6 GP7 GP8 GP9 GND SCK MOSI MISO GP13 GND GP14 GP15
VBUS VSYS GND 3V3_EN 3V3 (OUT) ADC_VREF GP28 GND GP27 GP26 RST GP22 GND GP21 GP20 GP19 GP18 GND GP17 GP16
SWCLK GND SWDIO

OPTO-COUPLER


USB PORT
RP2-80
12.00 MHz
Raspberry Pi Pico
GP0 GP1 GND GP2 GP3 GP4 GP5 GND GP6 GP7 GP8 GP9 GND SCK MOSI MISO GP13 GND GP14 GP15
VBUS VSYS GND 3V3_EN 3V3 (OUT) ADC_VREF GP28 GND GP27 GP26 RST GP22 GND GP21 GP20 GP19 GP18 GND GP17 GP16
SWCLK GND SWDIO

SWITCH

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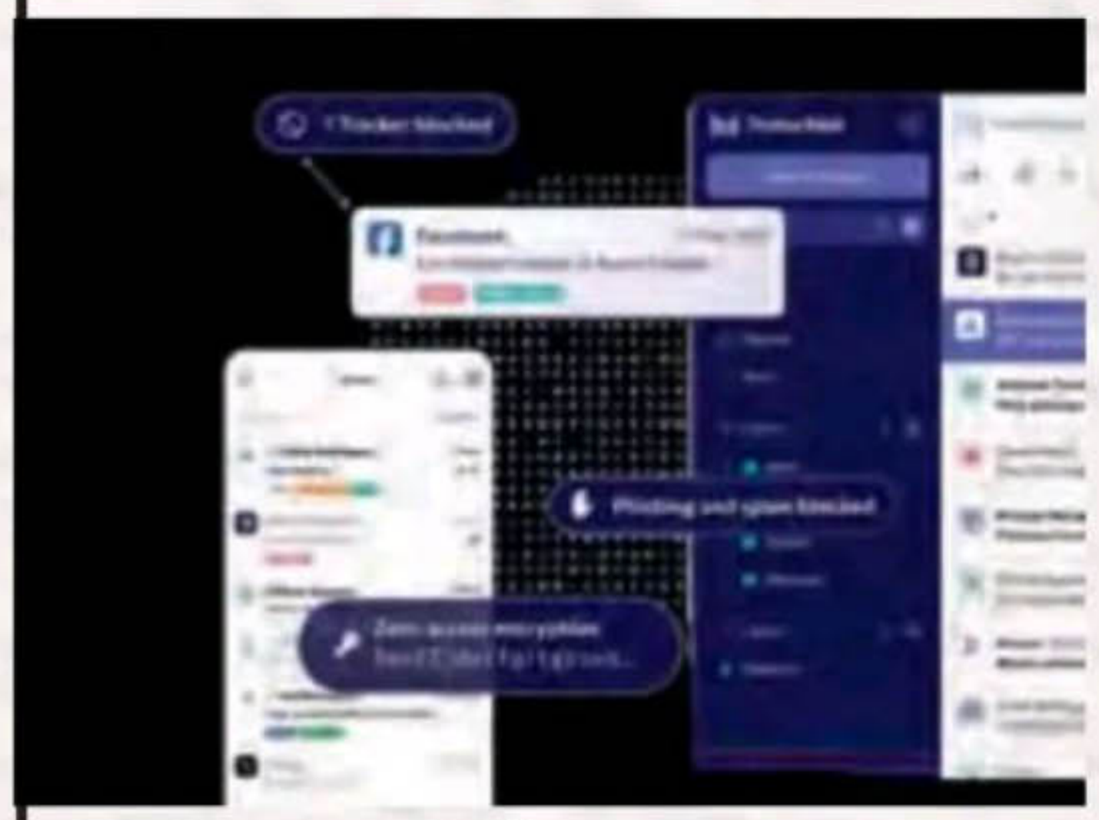
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S1
S2
S3
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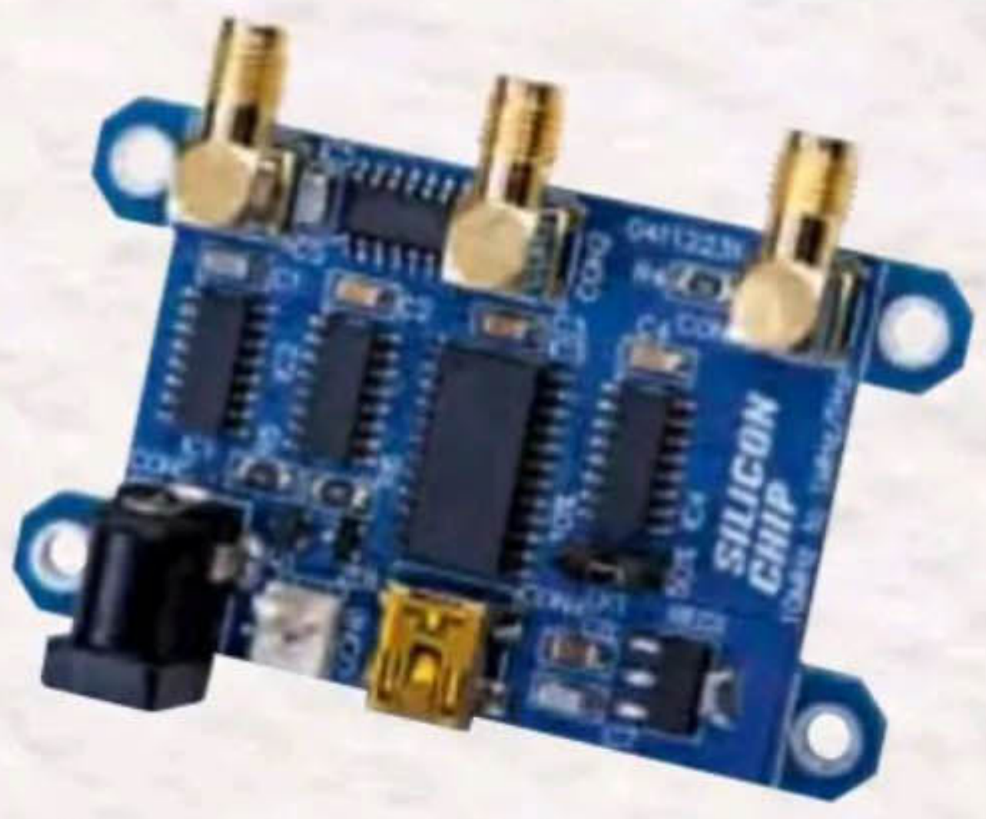

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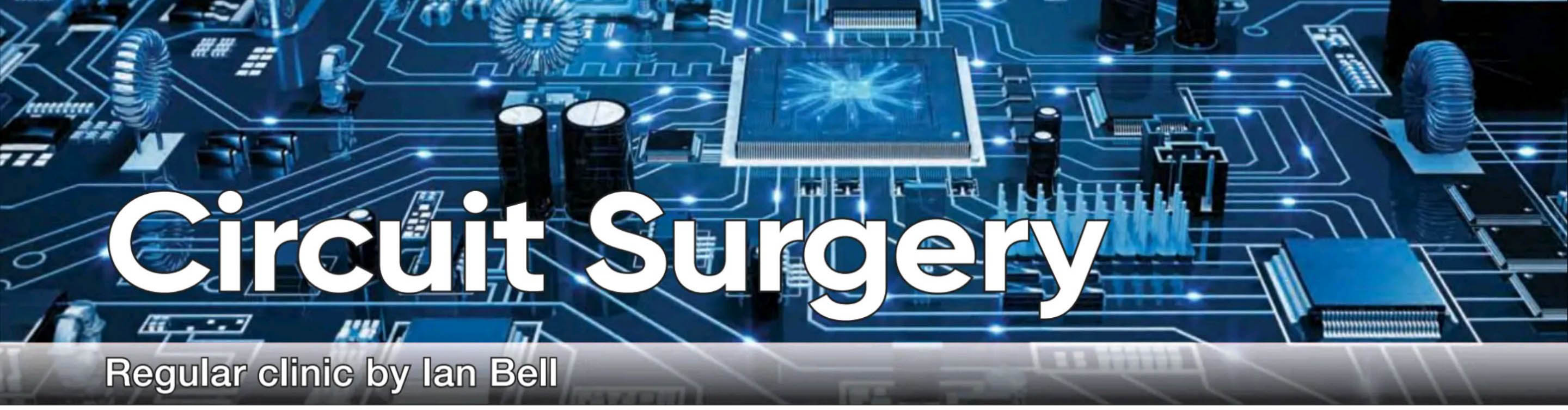


Circuit Surgery

Regular clinic by Ian Bell

Topics in digital signal processing – Filter Requirements

We are looking at various topics related to digital signal processing (DSP).

DSP covers a wide range of electronics applications where signals are manipulated, analysed, generated, stored or displayed as digital data. However, they usually originate from and/or end up as real-world signals for interaction with humans or other parts of the physical world.

Fig.1 shows the key elements of a generic DSP system with a signal path from an analogue input via digital processing to an analogue output. This does not necessarily represent every DSP system (not all have all the parts shown), but it serves are as reference for the various subsystems we will look at.

Last month, we covered some key topics in DSP relating to the frequency domain view of sampled signals. To depict the frequency domain, we used graphs of signal strength versus frequency – the signal's spectrum.

We also plotted parameters such as the gain of a circuit against frequency as a frequency response graph. Looking at frequency responses and signal spectra together shows us the effect circuits or signal processing will have on a signal and helps us understand design requirements.

This month, we will look at some aspects of how the spectra of sampled signals informs the requirements for the filters required at the inputs and outputs of DSP systems – the antialiasing and reconstruction filters shown in Fig.1.

Frequency Domain Recap

Our discussion last month concluded with a graph of the spectrum of a generic sampled signal. A similar example is shown in Fig.2. In this example, we show a signal where the original spectrum of the signal extends from DC to 20kHz (Fig.2a).

This shape is used to represent a general signal which has frequency content from DC to 20kHz. It could be audio, which has frequencies in this range, but here we are not being specific about what the signal is.

The spectrum of a 50kHz sampling signal (an impulse train) is shown in Fig.2b. As discussed last month, the spectrum contains single-frequency peaks (impulses) at integer multiples of the sampling frequency.

Mathematically, the sampled signal's spectrum can be obtained by convoluting the sampled and sampling signals' spectra –the result is shown in Fig.2c. This is because the two signals are multiplied together (in the time domain), which corresponds to convolution in the frequency domain.

Convolution has a reputation for being a difficult mathematical concept and, as we have said, DSP in general is a maths-heavy topic. We are avoiding getting into too much detailed mathematics in this series, but will be highlighting a few of the key ideas.

Last month, we referenced a YouTube video that shows some graphical representations of convolution. Another video, which readers with some mathematical background (functions, calculus) who are interested in convolution might find useful is from Professor Iain Collings (https://youtu.be/RmePGKWOSMQ).

It considers the continuous case, rather than the simplified discrete example we looked at. The video starts with the impulse response – another important concept in signal processing.

We previously discussed impulses, which are idealised zero-length pulses with specific areas under the pulse. An impulse response is the output a circuit produces with single impulse applied to the input, something we will mention again later.

Sampled Signal Spectra Examples

For considering general, straightforward cases of sampled signals in the frequency domain, you do not have to perform detailed convolution calculations. As can be seen in Fig.2c, sampling a signal at a constant sampling rate (f_s) results in the spectrum of the sampled signal being replicated at integer multiples of f_s. These are referred to as replica spectra or spectral images.

We can use this fact to visualize spectra of sampled signals under different scenarios, and look at the implications for the design of DSP systems.

Consider what happens if we lower the sampling frequency in the Fig.2 example to 40kHz and 35kHz. The 40kHz

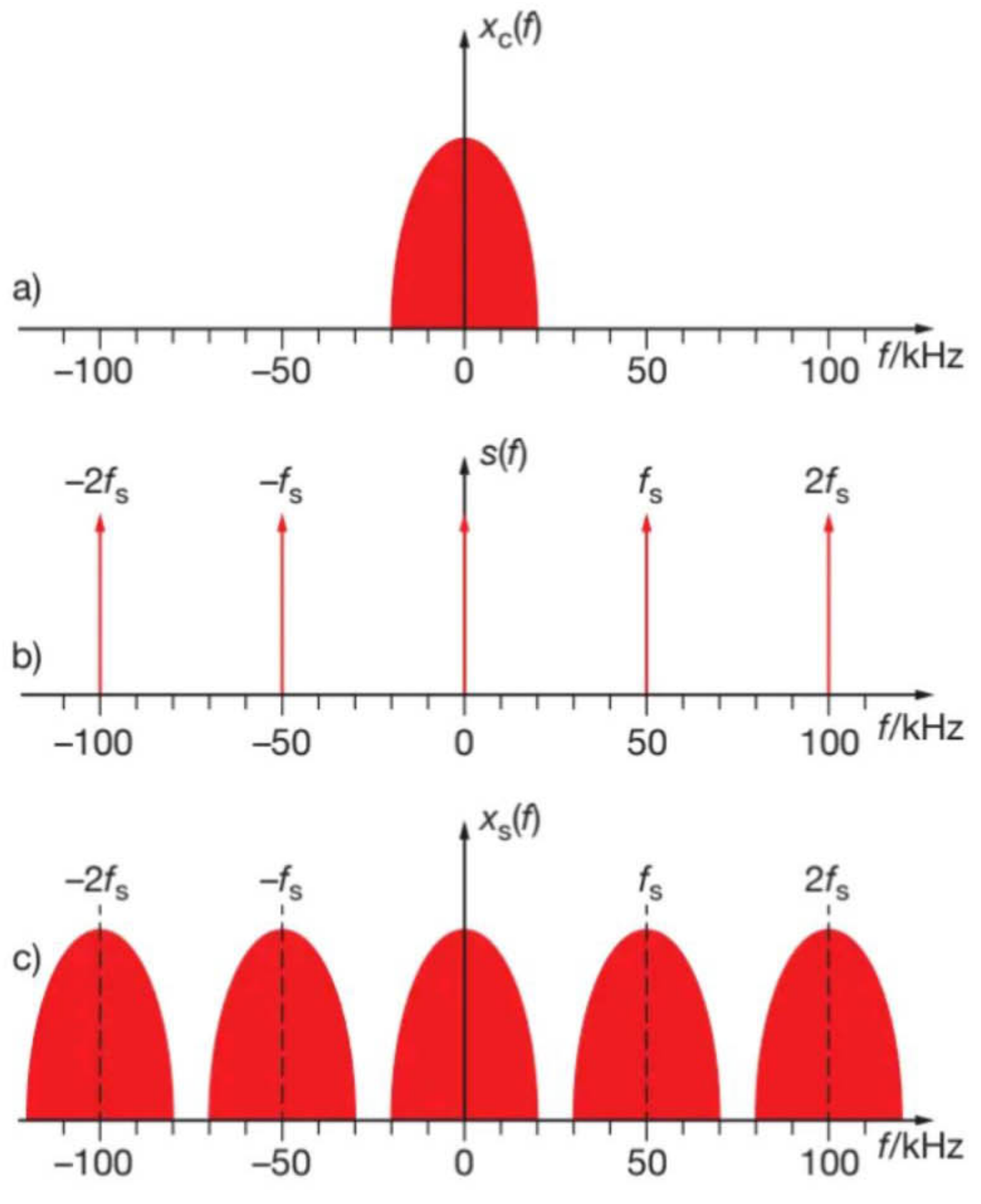


Fig.2: Frequency domain views of a sampled signal: (a) original continuous time signal; (b) sampling signal spectrum; (c) sampled signal spectrum.

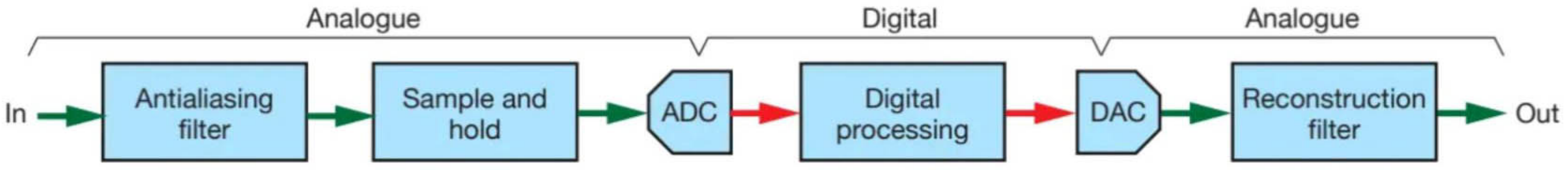


Fig.1: A generic digital signal processing (DSP) system structure.

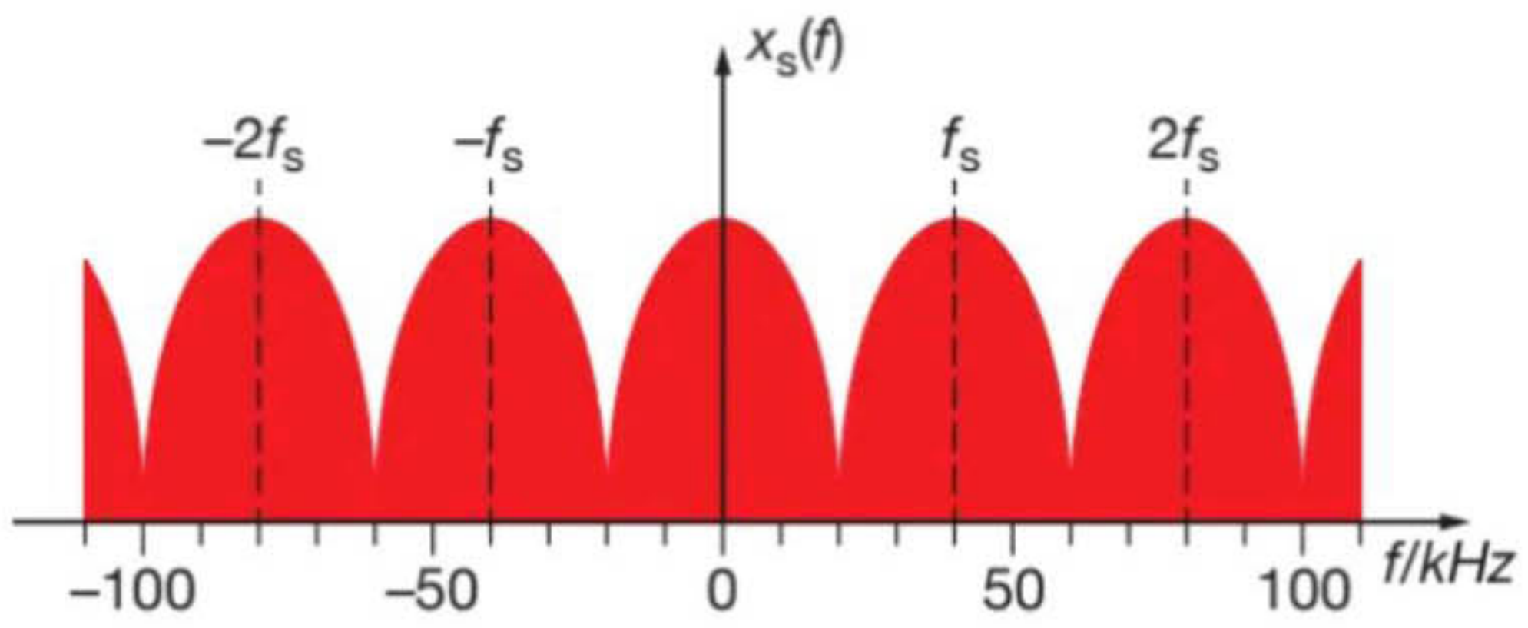


Fig.3: A variation of the spectrum in Fig.2(c), where the sampling frequency is reduced to 40kHz.

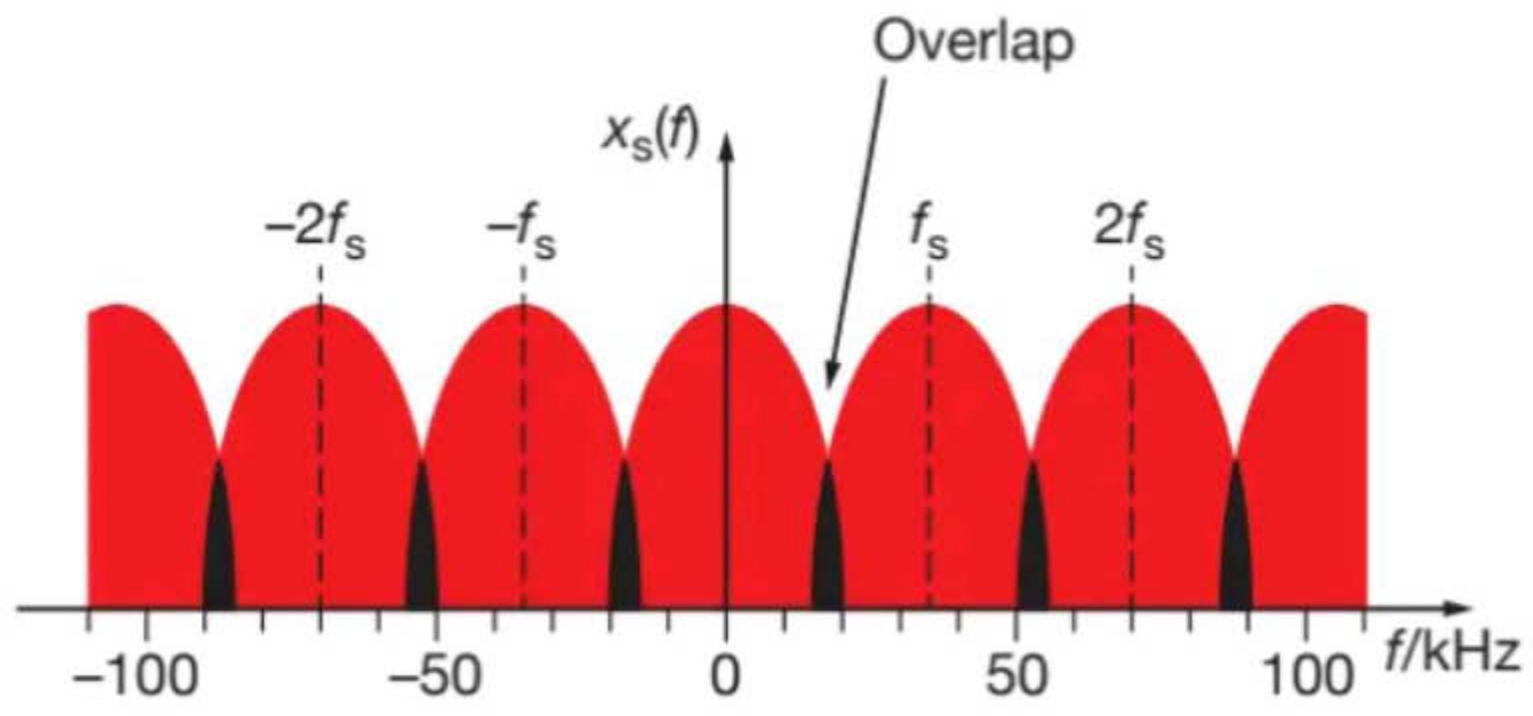


Fig.4: A variation of the spectrum in Fig.2(c), where the sampling frequency is reduced to 35kHz. The overlapping ranges are highlighted.

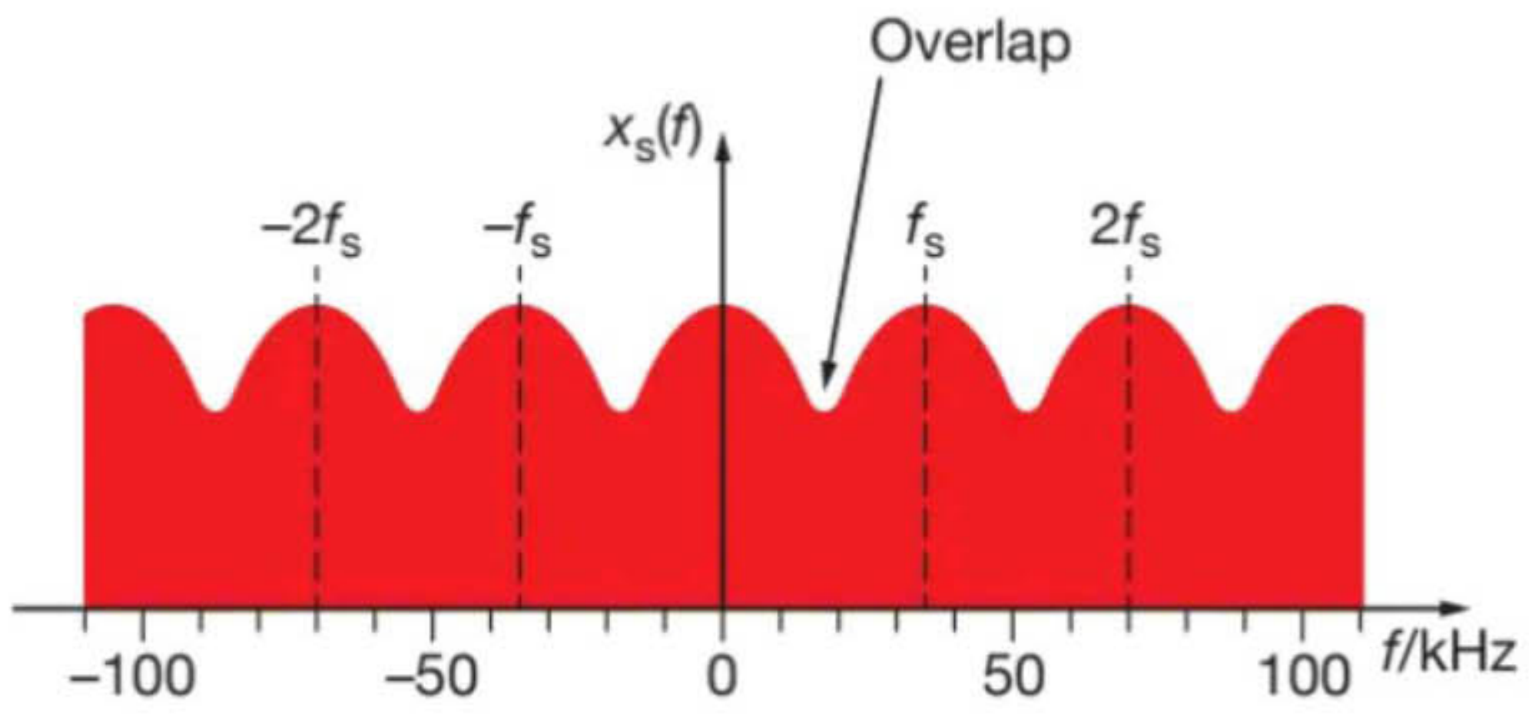


Fig.5: A sketch of an actual spectrum resulting from the situation in Fig.4, with the overlapping signals combining.

sampling frequency case is shown in Fig.3, where we see that the replicated spectra (spectral images) of the original signal in the sampled signal abut one another in spectrum but are separate.

Due to the replicated spectra being closer together, we can now see part of the copies at $+3f_s$ and $-3f_s$ in the range plotted in Fig.3.

The 35kHz sampling frequency case is shown in Figs.4 & 5. Fig.4 shows the replicas of the original spectra individually, with the ranges where they overlap highlighted. In the overlap ranges, the contributions of two the spectra add up, so the overall spectrum will look something like the one in Fig.5 – this is a sketch, it was not accurately calculated.

The labelled overlap in Fig.4 ranges from $f_s - B$, where B is the bandwidth (maximum frequency) of the input signal, to B, which is 15-20kHz in this example. Other overlaps in the spectrum are at the same positions relative to the various replicas of the sampled signal.

Looking at the spectra in Figs. 2c & 3, we can imagine that it is straightforward to obtain the original spectrum of the continuous signal, and hence an exact copy of the original signal, by applying a filter that can remove all the frequencies not in the original signal.

This is the role of the reconstruction filter shown in Fig.1. There are some additional considerations due to the DAC output not being an ideal impulse train. We will discuss that in a later article; for now, assume that we are filtering an ideal sampled signal in form of a weighted impulse train – see Fig.6. For more detail on this, refer to the discussion relating to Fig.10 in last month's article.

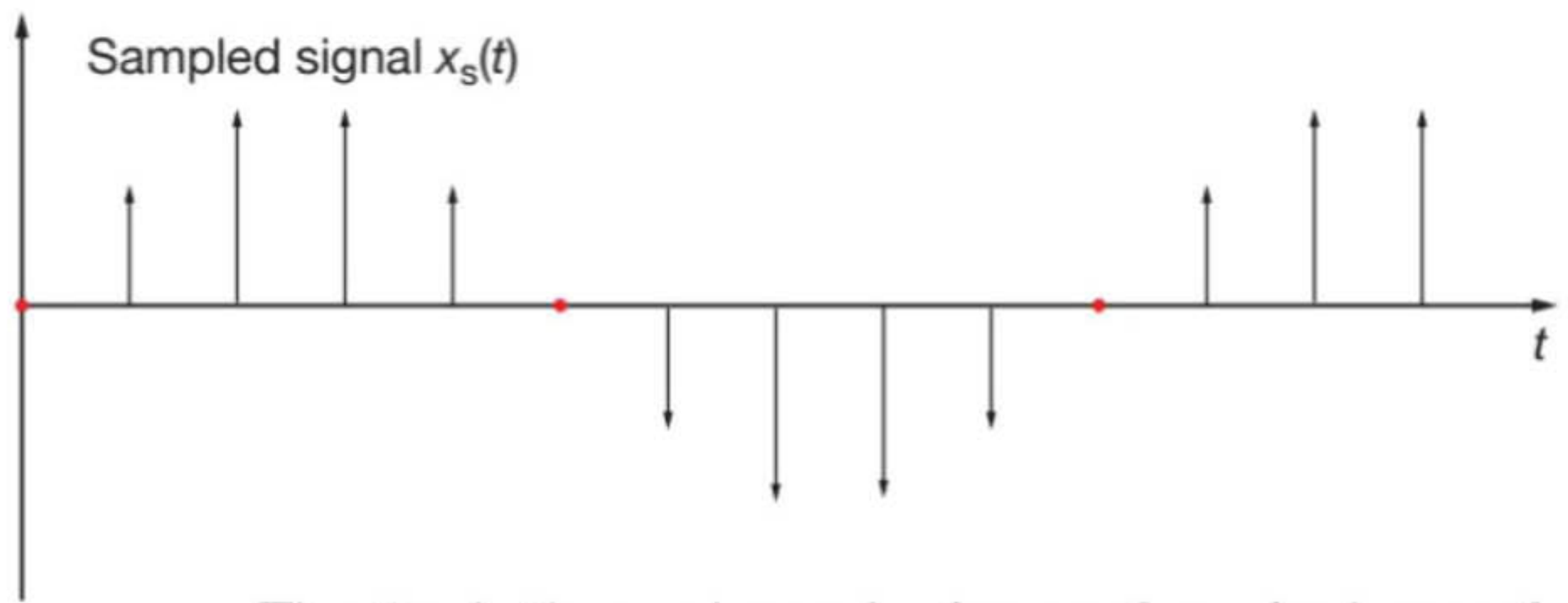


Fig.6: A time domain (waveform) view of a sampled signal.

The fact that it is possible (at least in theory) to perfectly recover a correctly sampled continuous signal from the sampled data is an important concept in DSP.

That applies to the simple cases shown here, where the there is no actual processing (we are just looking at the pure sampled signals), but also to digitally-processed (eg, filtered) and digitally-created (synthesised) sampled signals, as long as the requirements discussed below are met.

Of course, absolutely perfect reconstruction of a continuous signal from samples requires ideal circuitry and will not be achieved in practice; however, with good design, very high performance is possible.

Reconstruction Filtering Examples

An ideal low pass filter with a cutoff of $f_s/2$ can do a perfect job of recovering or reconstructing the original continuous signal from a correctly sampled signal, as shown in Figs.7 & 8

For the situation in Fig.7, the cutoff frequency is 25kHz and there is some 'headroom' between this and maximum signal frequency of 20kHz. For the situation in Fig.8, the cutoff frequency is 20kHz, which is equal to the maximum signal frequency of 20kHz – there is no headroom, and we definitely need an ideal filter to achieve this.

Ideal filters have infinitely fast cut-off (sometimes referred to as "brick wall" filters for this reason), which is not possible in reality. We will discuss the implications of this in more detail shortly.

If we attempt to recover the sampled signal shown in Fig.5 using an ideal low pass filter with a cutoff of $f_s/2$ (17.5kHz in this case), we fail to obtain the original continuous signal. This is shown in Fig.9, where the difference in the shape of the spectrum from Fig.2a can be observed.

A different spectrum means a different continuous time waveform and hence failure to reconstruct the sampled signal. The overlapping parts of the spectrum with the replicas produces additional frequency content in range of 15kHz to 17.5kHz, where the overlap region is inside the filter's pass band.

The original signal bandwidth was 20kHz, so perhaps we should use an ideal filter with this cutoff – however, that will not help reconstruct the signal correctly, as the extra bandwidth is also in the overlap range and will contain

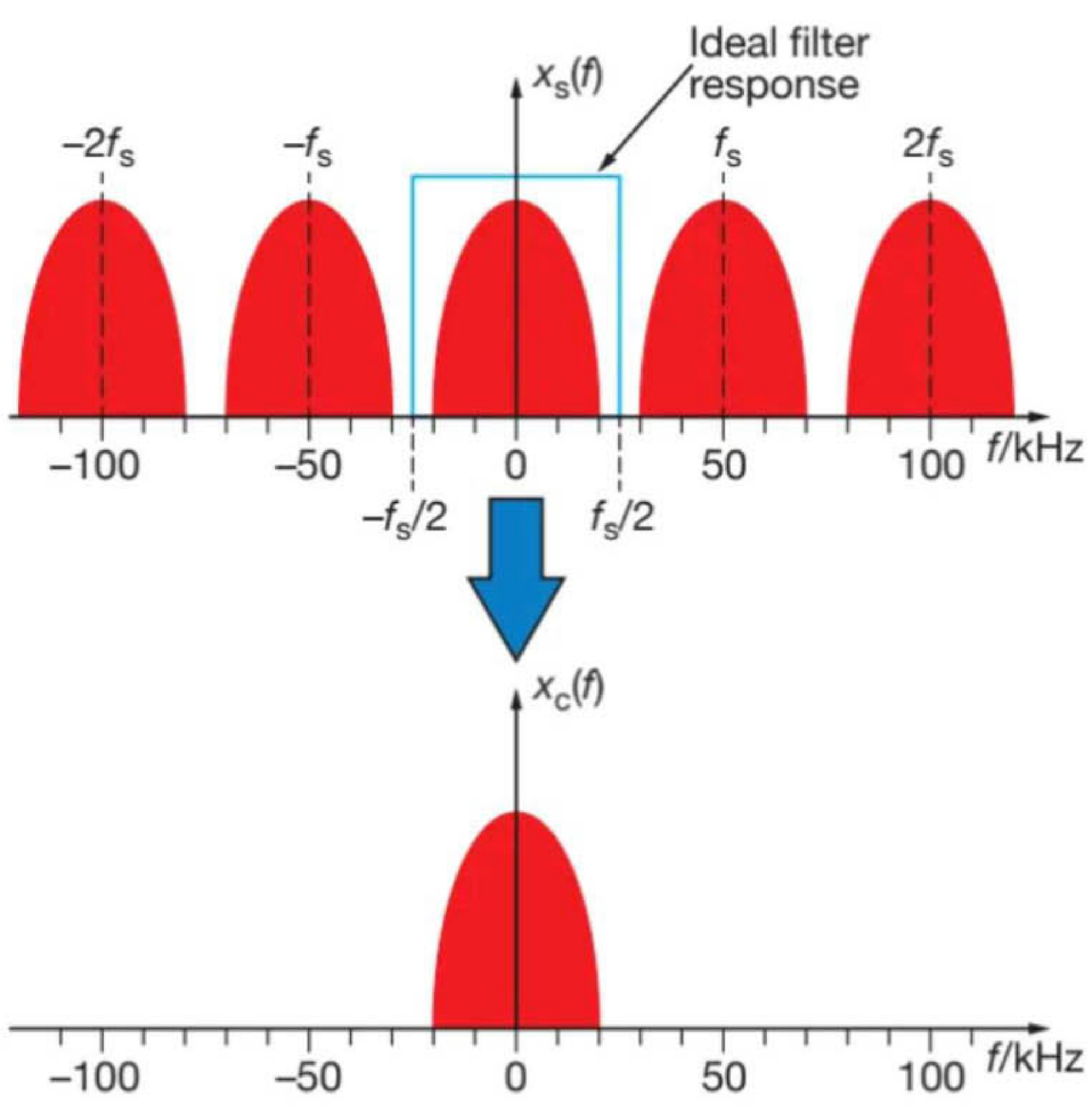


Fig.7: Filtering the sampled signal spectrum from Fig.2c with an ideal filter to recover the original continuous signal (Fig.2a).

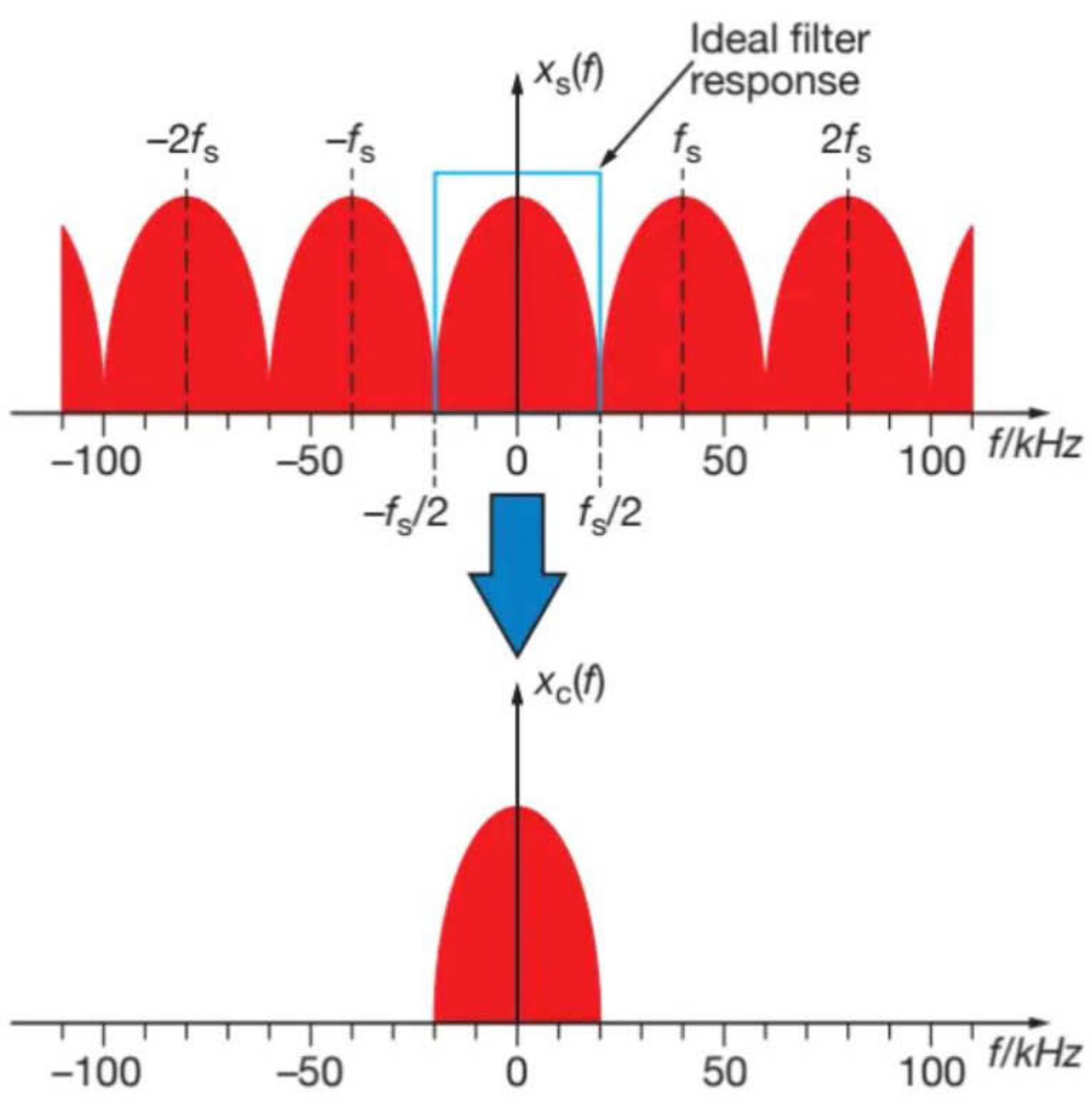


Fig.8: Filtering the sampled signal spectrum from Fig.3 with an ideal filter to recover the original continuous signal (Fig.2a).

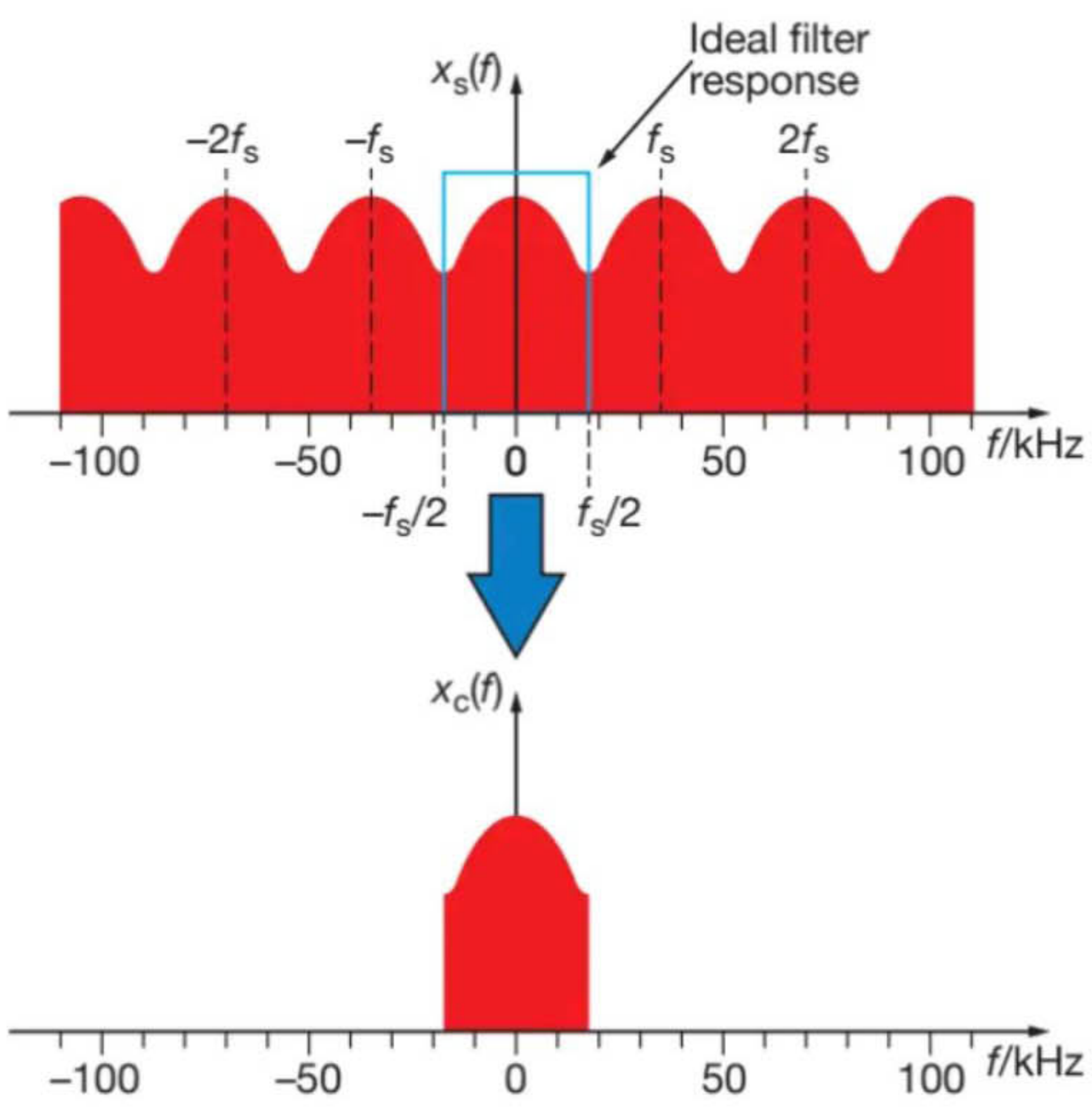


Fig.9: Filtering the sampled signal spectrum from Fig. with an ideal filter fails to recover the original continuous signal (Fig.2a).

additional frequency content. It is not possible to define a filter that will recover the signal correctly in this case.

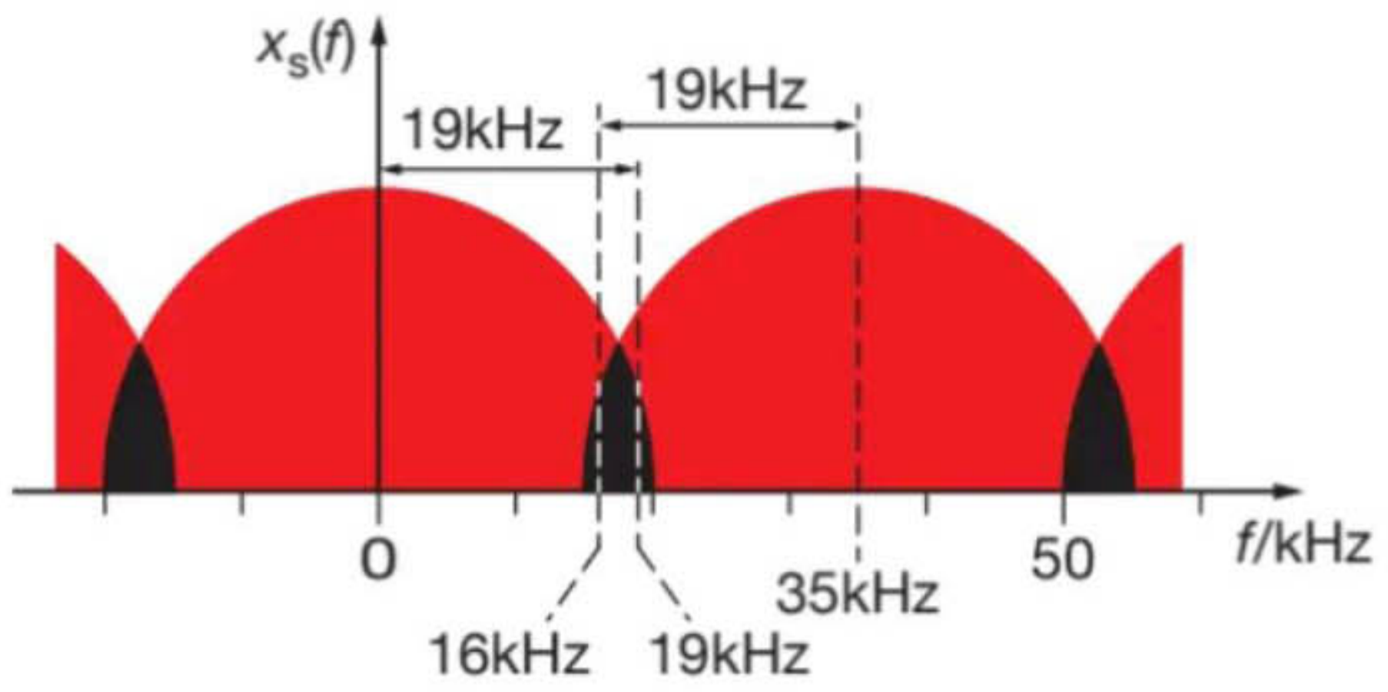


Fig.10: A 19kHz component in the original signal produces an unwanted 16kHz signal due to the limited 35kHz sampling rate.

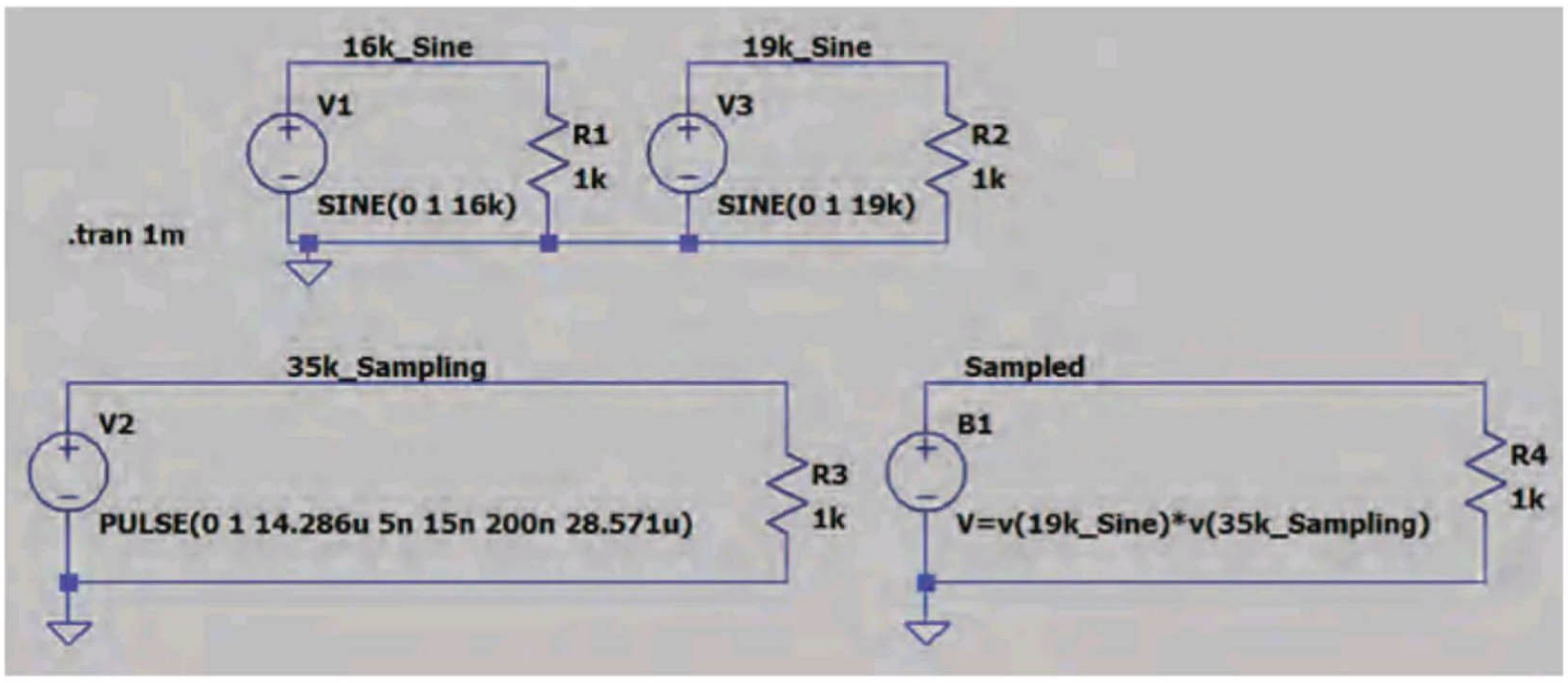


Fig.11: An LTspice schematic for simulating aliasing examples.

Nyquist and Aliasing in the Frequency Domain

In the first article in this series (May 2024), we discussed the Nyquist-Shannon sampling theorem and the concept of aliasing. The theory shows that if the input does not contain any frequency components at or beyond half the sampling frequency, it is possible to perfectly reproduce the original signal from the sample data.

The scenarios shown in Figs.7 & 8 meet the Nyquist sampling requirement. When we look at the spectra, we see that sampled signal can be reconstructed correctly if a suitable reconstruction filter is used.

If the Nyquist sampling requirement is not met, the sampled data is ambiguous; that is, there could be more than one signal that results in the same set of sample values. Therefore, signals reconstructed from the sampled data will not match the original input.

This ambiguity is called aliasing – one signal is an alias of the other, and they cannot be distinguished. The discussion in the May article just looked at the time domain signals. Now we have seen how this problem manifests in the frequency domain.

For the scenario in Fig.9, the Nyquist sampling requirement is not met, so the signal is aliased.

The labelled overlap region shown in Figs.4 & 5 runs from 15kHz, which is the sample frequency minus the maximum input signal frequency of 20kHz (35kHz – 20kHz = 15kHz). This overlap range ends at 20kHz (the maximum input signal frequency).

Fig.10 shows a zoom-in on part of Fig.4 in which one aliased frequency from the original signal (19kHz) is highlighted.

For the replica spectrum centred on f_s, the 19kHz component of the original signal (which has components at ±19kHz due to the symmetry of the spectrum in negative frequencies) produces replicas at f_s ±19kHz, that is at 35kHz - 19kHz = 16kHz and 35kHz + 19kHz = 54kHz.

Here we consider the 16kHz signal, which is inside the original sampled signal bandwidth of 20kHz – it is therefore an alias signal.

If we filter the sampled signal with an ideal low-pass filter with a cut-off frequency 20kHz, the alias of 19kHz at 16kHz would not be removed by the filter, but it should not be there – it was not in the original sampled signal.

Fig.11 shows an LTspice circuit that can demonstrate the aliasing situation just discussed in the time domain. This is similar to the example in the May issue, but with signals relevant to the current example.

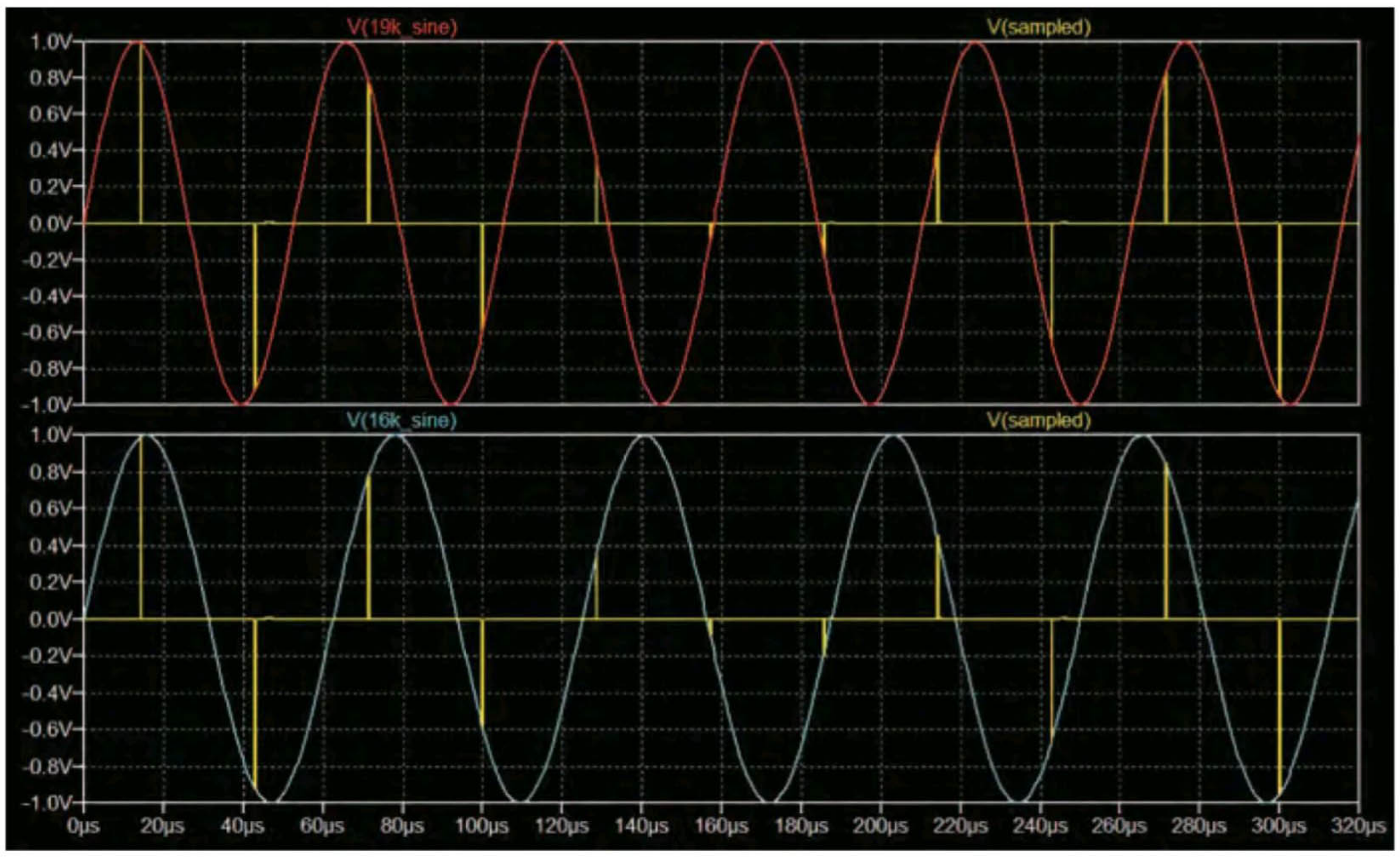


Fig.12: The results of simulating the circuits shown in Fig.11.

Sinewaves at 19kHz and 16kHz are generated. The 19kHz waveform is sampled at 35kHz. This is achieved by multiplying the sinewave from source V3 by the sample pulse train from source V2 using behavioural source B1.

The top trace in Fig.12, plotted by the simulation of Fig.11, shows the 19kHz waveform and the samples obtained from it. 19kHz is beyond the Nyquist rate of 17.5kHz for 35kHz sampling, so aliasing will occur, with an alias at 16kHz.

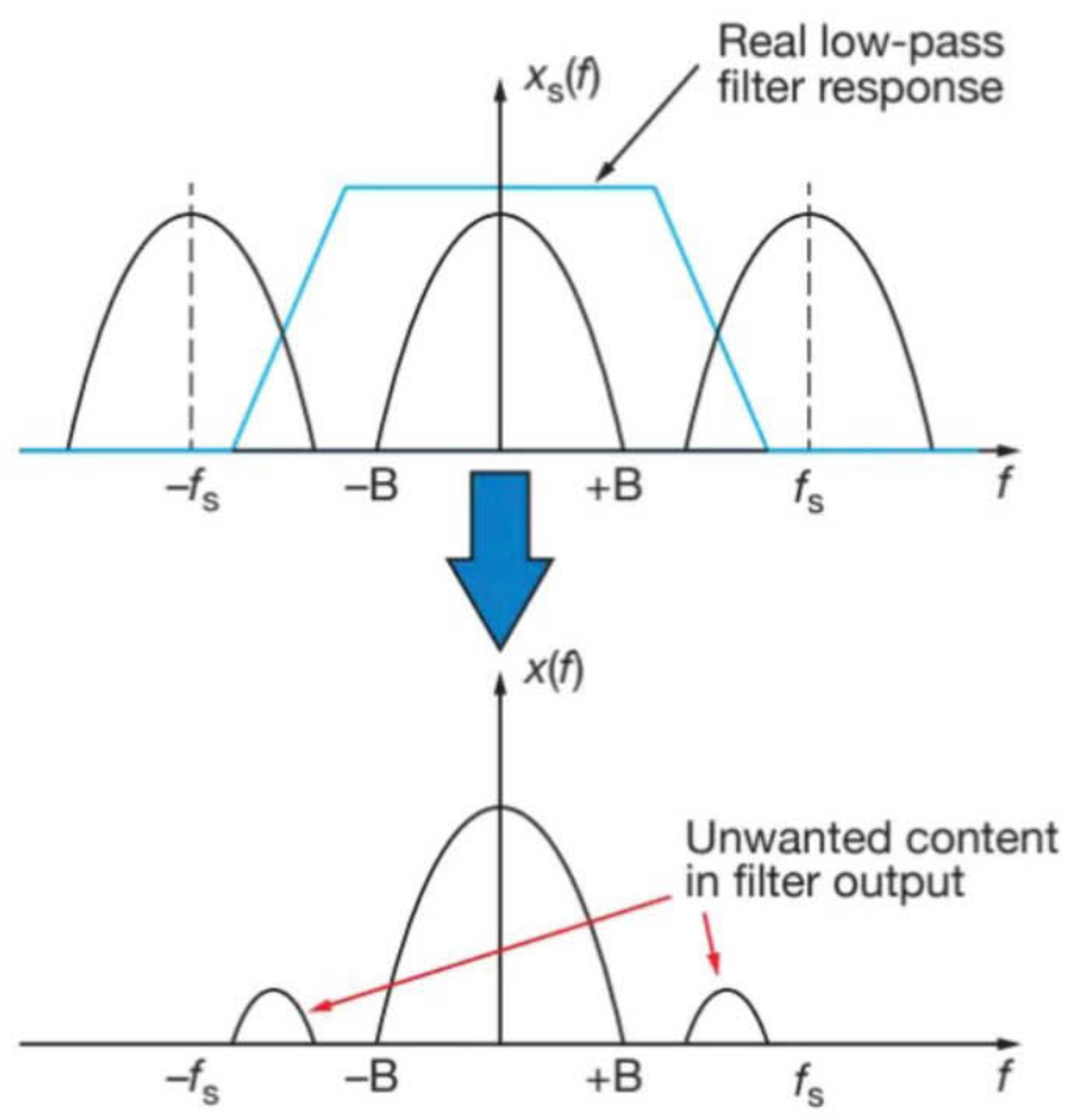
The bottom trace in Fig.12 shows the 16kHz waveform together with the samples from the 19kHz waveform. All the samples are exactly on points on the 16kHz waveform, showing that the same set of samples could have been obtained from either a 16kHz or 19kHz waveform.

Reconstruction Filter Requirements

If we sample a signal with frequency content right up to the Nyquist rate (just less than half the sampling frequency, as in Fig.8), no aliasing occurs in the sampling process. However, the signal can only be recovered using an ideal “brick wall” reconstruction filter (as shown in Fig.8), which is impossible to do in practice.

If the sampling frequency is above the Nyquist rate, there is some headroom, as shown in Fig.7. However, this does not guarantee that the signal can be perfectly reconstructed. Ideally, the filter must completely remove the replica spectra, but the closer the sampling rate is to the Nyquist rate, the more demanding the filtering requirements become.

That is why it’s common for audio to be sampled at either 44.1kHz or 48kHz when the highest frequency that’s intended to be reproduced is 20kHz. That gives 4.1kHz or 8kHz of headroom, allowing the reconstruction filters to have very little attenuation up to 20kHz, but



$x_s(f)$
Real low-pass filter response
$-f_s$
$-B$
$+B$
f_s
f
$x(f)$
Unwanted content in filter output
$-f_s$
$-B$
$+B$
f_s
f

Fig.13: Filtering a sampled signal with a non-ideal reconstruction filter may result in unwanted frequency content in the output due to imperfect reconstruction.

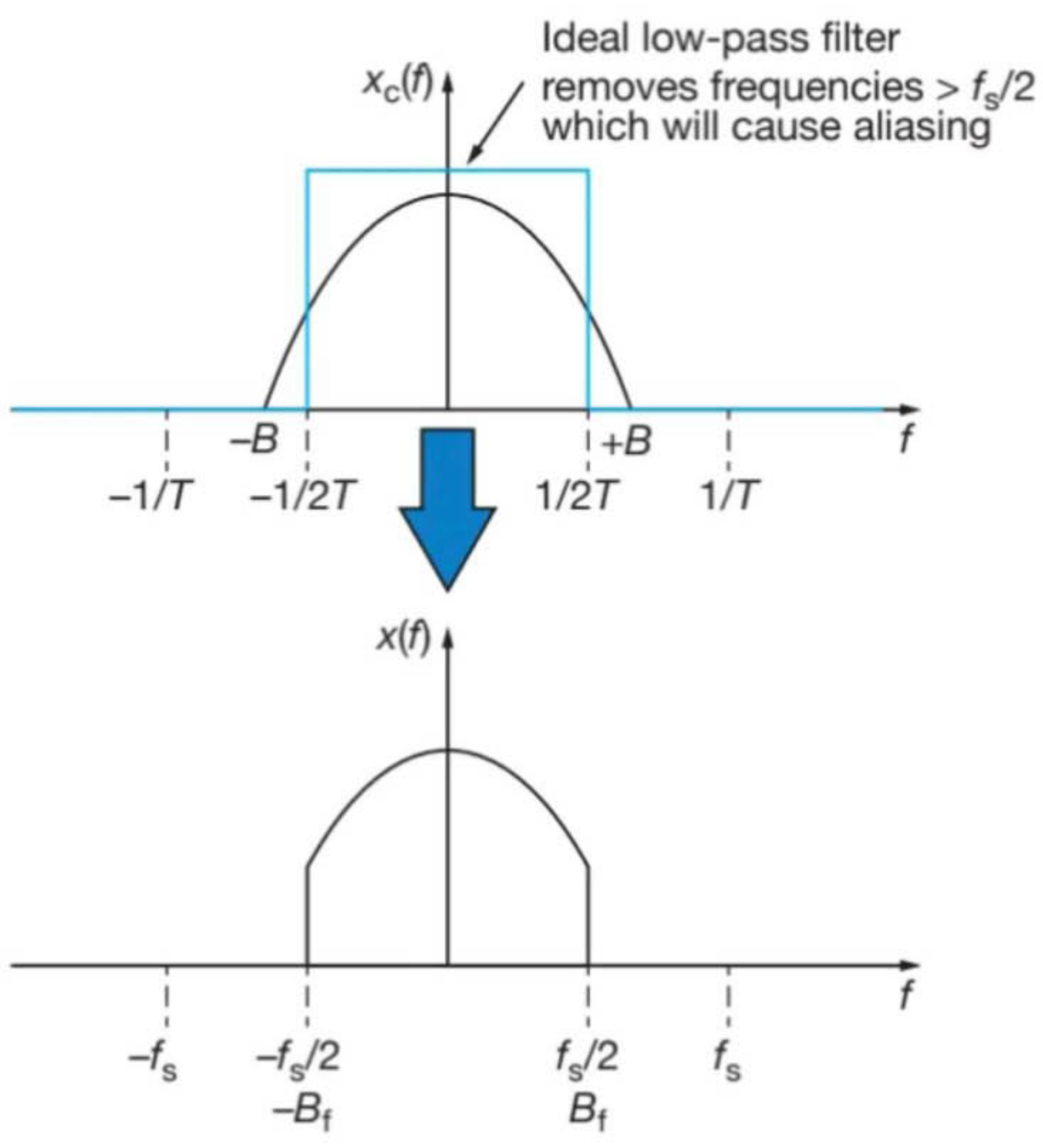
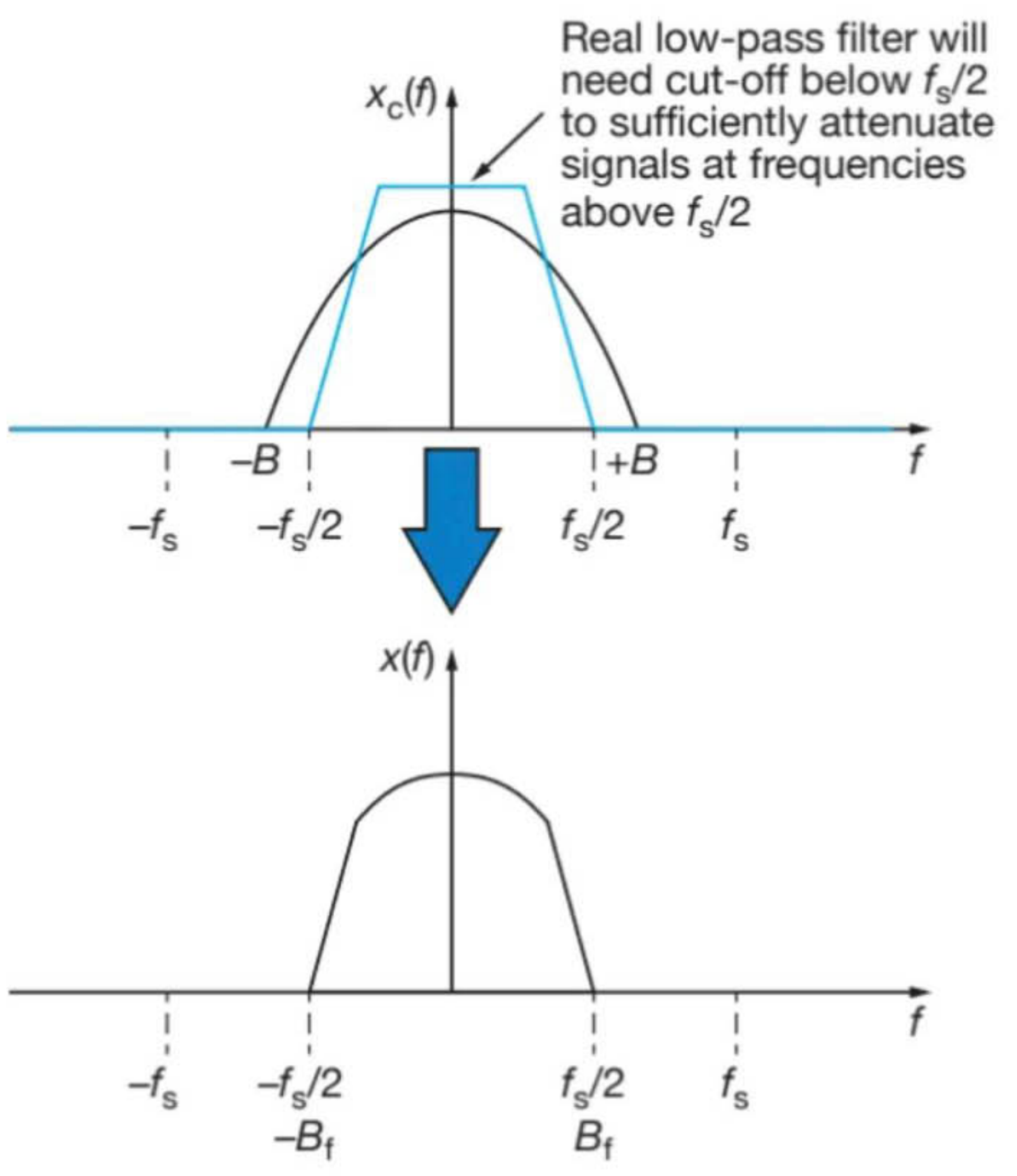


Fig.14: Filtering a continuous signal with an ideal antialiasing filter.



$x_c(f)$
Real low-pass filter will need cut-off below $f_s/2$ to sufficiently attenuate signals at frequencies above $f_s/2$
$-B$
$+B$
$-f_s$
$-f_s/2$
$f_s/2$
f_s
f
$x(f)$
$-f_s$
$-f_s/2$
$-B_f$
$f_s/2$
B_f
f_s
f

Fig.15: Filtering a continuous signal with a realistic antialiasing filter.

significant attenuation from 22.05kHz or 24kHz and up.

The problem with trying to reproduce frequencies right up to the Nyquist limit is illustrated in Fig.13, which shows a case where a realistic reconstruction filter fails to remove part of the spectral images. The result is unwanted frequency content in the output, which means the output waveform will have a different shape from that implied by the sample data – the reconstruction is imperfect.

Antialiasing Filter Requirements

Similar challenges exist with the requirements for antialiasing filters. If we had an ideal filter, we could simply set the cut-off to be equal to the Nyquist rate, and that would remove any possibility of aliasing, as shown in Fig.14.

That figure shows a continuous signal spectrum which is to be sampled (like Fig.2a), with a bandwidth (*B*) extending beyond the Nyquist rate. Hence, it will cause aliasing. The filter removes all frequencies above half the sample rate ($f_s/2$) to produce a signal with a new bandwidth ($B_F = f_s/2$), which will not cause aliasing.

We cannot use an ideal filter in real designs, but we can use a cutoff frequency below the Nyquist rate so that the attenuation at the Nyquist frequency is sufficient not to cause any problems., as illustrated in Fig.15.

However, one problem here is that part of the signal that can be sampled correctly at the chosen sample rate is attenuated – the sampled signal will not be aliased, but it will not be a perfect representation of the original signal in the $\pm f_s/2$ bandwidth range.

The simplified example in Fig.15 shows all the unwanted content removed, but a real filter may not be able to achieve that, resulting in some level of aliasing. Changing the filter characteristics will control how much the parts of the signal that can be correctly sampled are unfortunately removed, and how much aliasing occurs.

If the signal content above the Nyquist frequency (particularly close to the Nyquist frequency) is not strong, the filtering requirements are less demanding. So it is important (if possible) to have a good understanding of the frequency content of the signal being sampled to guide the antialiasing filter design.

Both antialiasing and reconstruction filters require trade-offs. Filters with very sharp cut-offs are larger, more complex and more expensive than lower-performance filters, but provide better signal quality into and out of the DSP system.

Increasing the sample frequency (for a given input signal bandwidth) reduces the demand on the filtering, as there is larger range up to the Nyquist rate, over which the filter's gain can decrease without affecting the wanted signal.

This means lower-performance filters can be used, or a filter cut-off rate suitable for a lower sampling rate will give better quality. However, a higher sample rate increases the demands on other parts of the system (faster ADCs and DACs, more data to handle at a faster rate) so such an approach has its own limitations. PE

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in Circuit Surgery.
The examples and files are available for download from the PE website: https://bit.ly/pe-downloads

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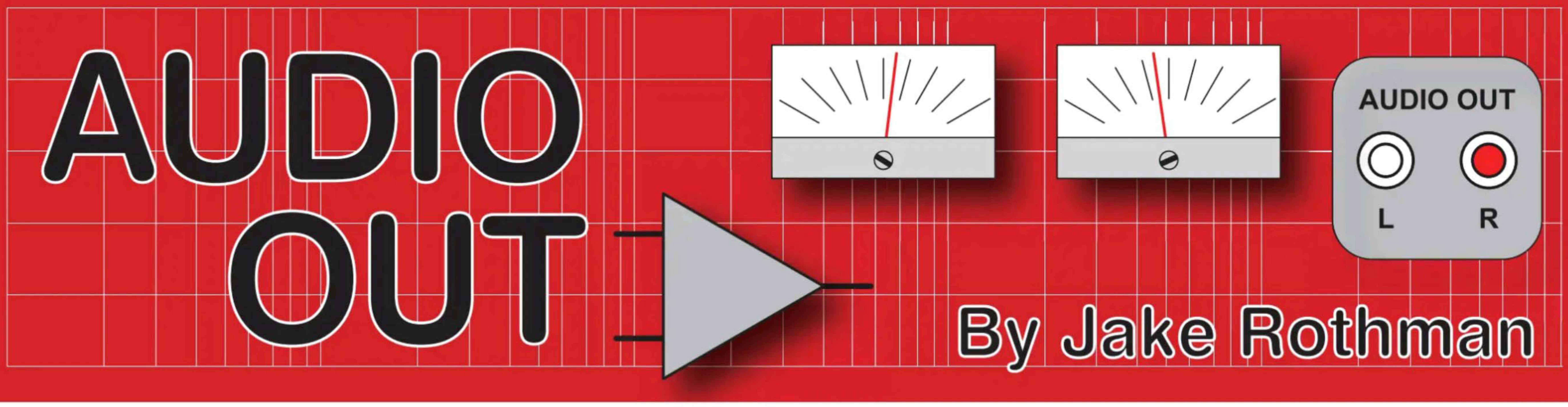


AUDIO OUT

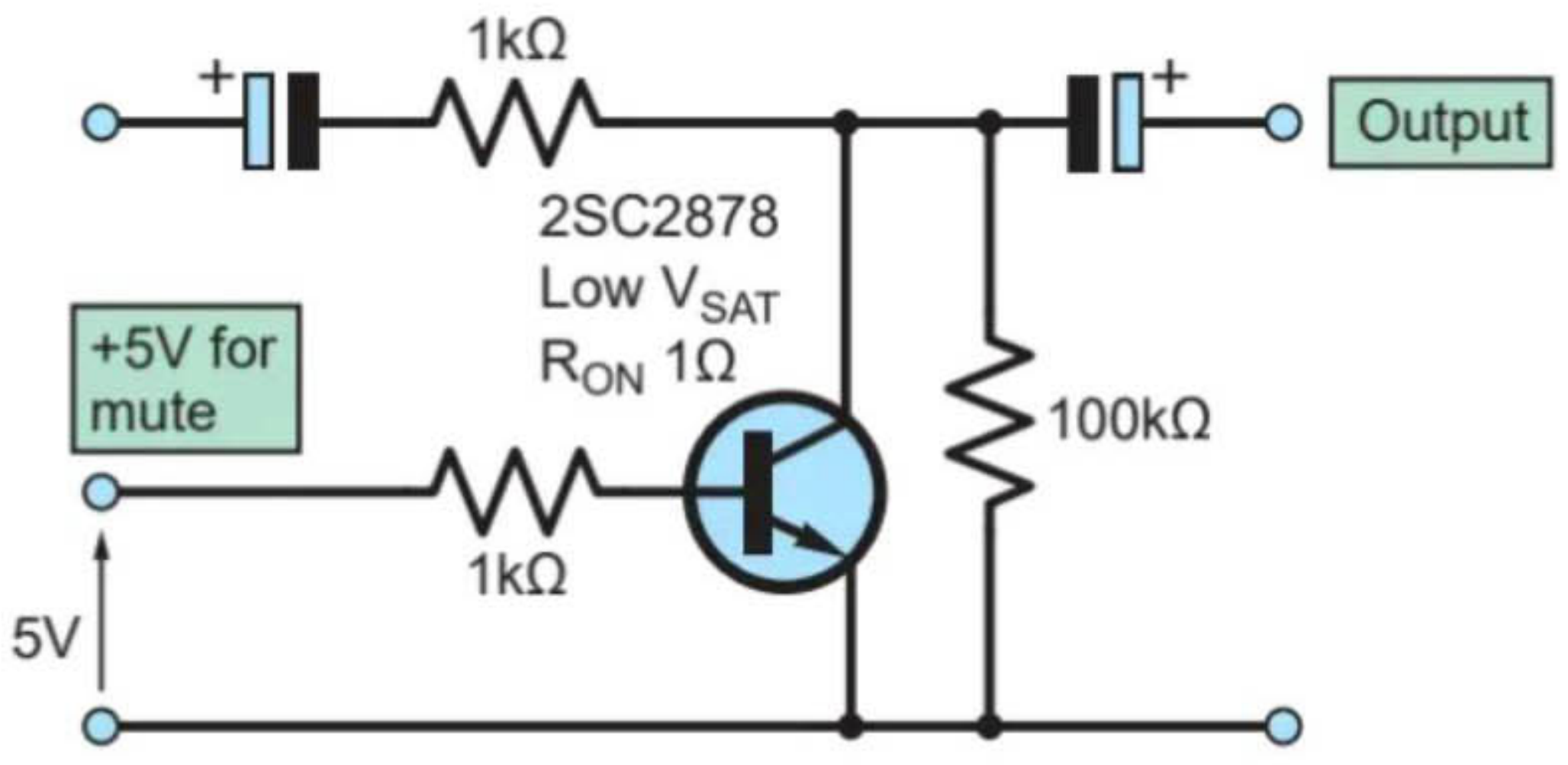
By Jake Rothman

Audio switching Part 4 – real electronic switching

We have been looking at the topic of audio switching for a few months now; this article (and the following one) will concentrate on solid-state switching techniques.

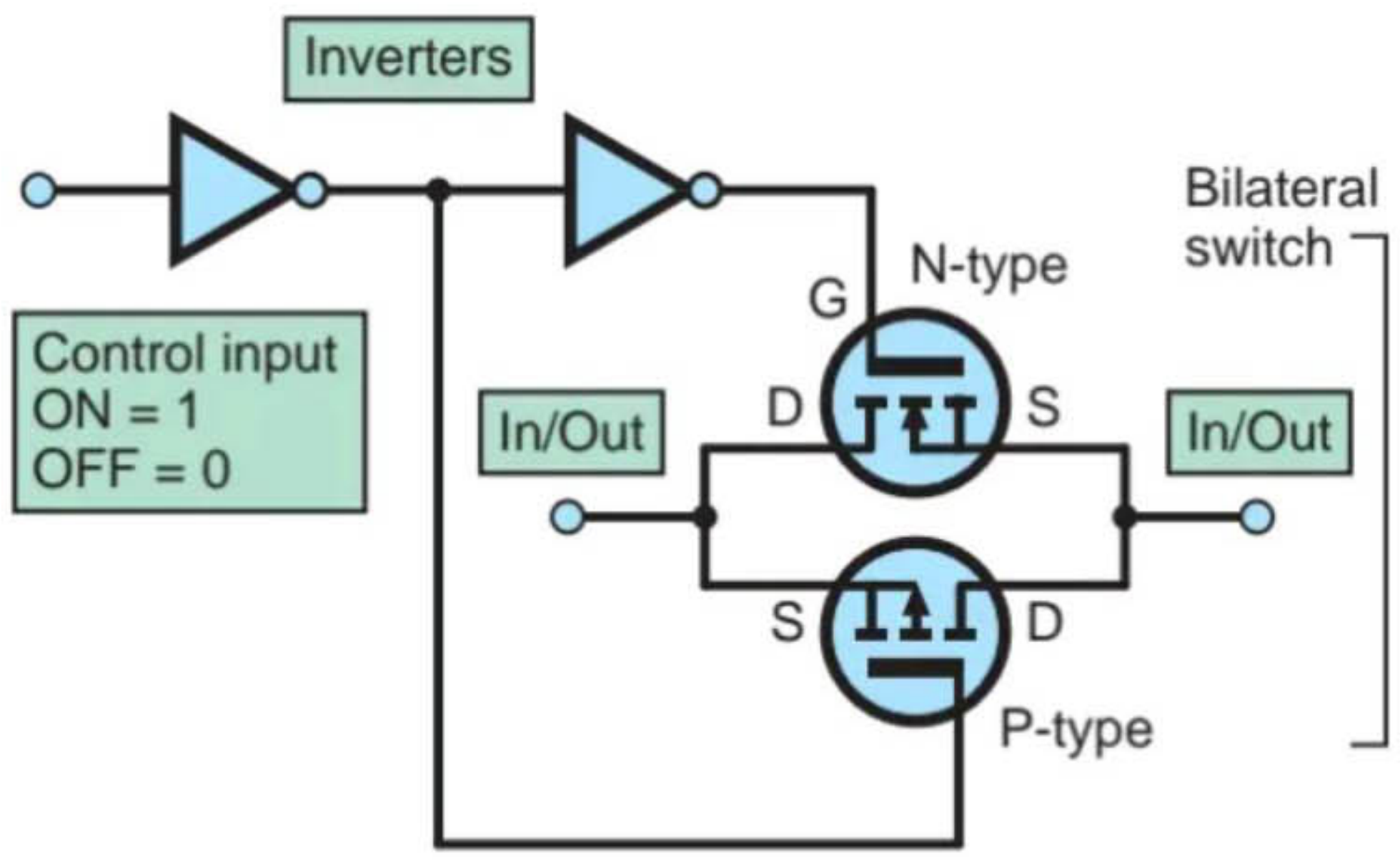
Switching audio signals with transistors is cheaper than mechanical switching (switches/relays) and increases flexibility. Disadvantages include increased distortion, control breakthrough and a limit near the power rails where signal breakthrough increases significantly.

The on-resistance (R_{ON}) is usually relatively high, and is modulated by the audio signal, which is one source of distortion. Also, the isolation is worse than a mechanical switch when it is off. These problems have not been eliminated, but they can be minimised with more advanced circuit design and the help of op amps.


1kΩ
+
+
Output
2SC2878
Low V_{SAT}
R_{ON} 1Ω
+5V for mute
1kΩ
100kΩ
5V

For negative operation use PNP type 2SC4213

Fig.63: bipolar transistors are only used for muting. Toshiba makes these transistors especially for muting (R_{ON} = 1Ω). Often, two stages are wired in cascade with 100Ω resistors rather than 1kΩ for lower output impedance.


Inverters
Control input
ON = 1
OFF = 0
G
N-type
Bilateral switch
In/Out
D
S
In/Out
S
D
P-type

Basic 4016 circuit

Fig.64: a bilateral switch. Two complementary lateral MOSFETs wired in parallel provide a degree of linearisation of the on-resistance.

Solid-state switching

The first solid-state switches used light-dependent resistors (LDRs) enclosed with a light source (originally a filament lamp, and later, LEDs). These were often home made but later produced as complete units called Vactrols (Fig.62).

These are still popular in some guitar effects pedals but are rather elusive and expensive. Also, cadmium sulfide* is banned under RoHS legislation. They offer very clean but slow (~100ms) switching. The current required to drive the LED is high, typically 10-20mA.

Bipolar transistors don't make good audio switches since they are unidirectional, and their base operating current contaminates the audio. They are only used for output muting, such as stopping a CD player output thumping upon turn-on, as shown in Fig.63.

FETs are the most common solid-state audio switch. MOSFETs can be bi-directional if a complementary N and P channel pair are paralleled; this

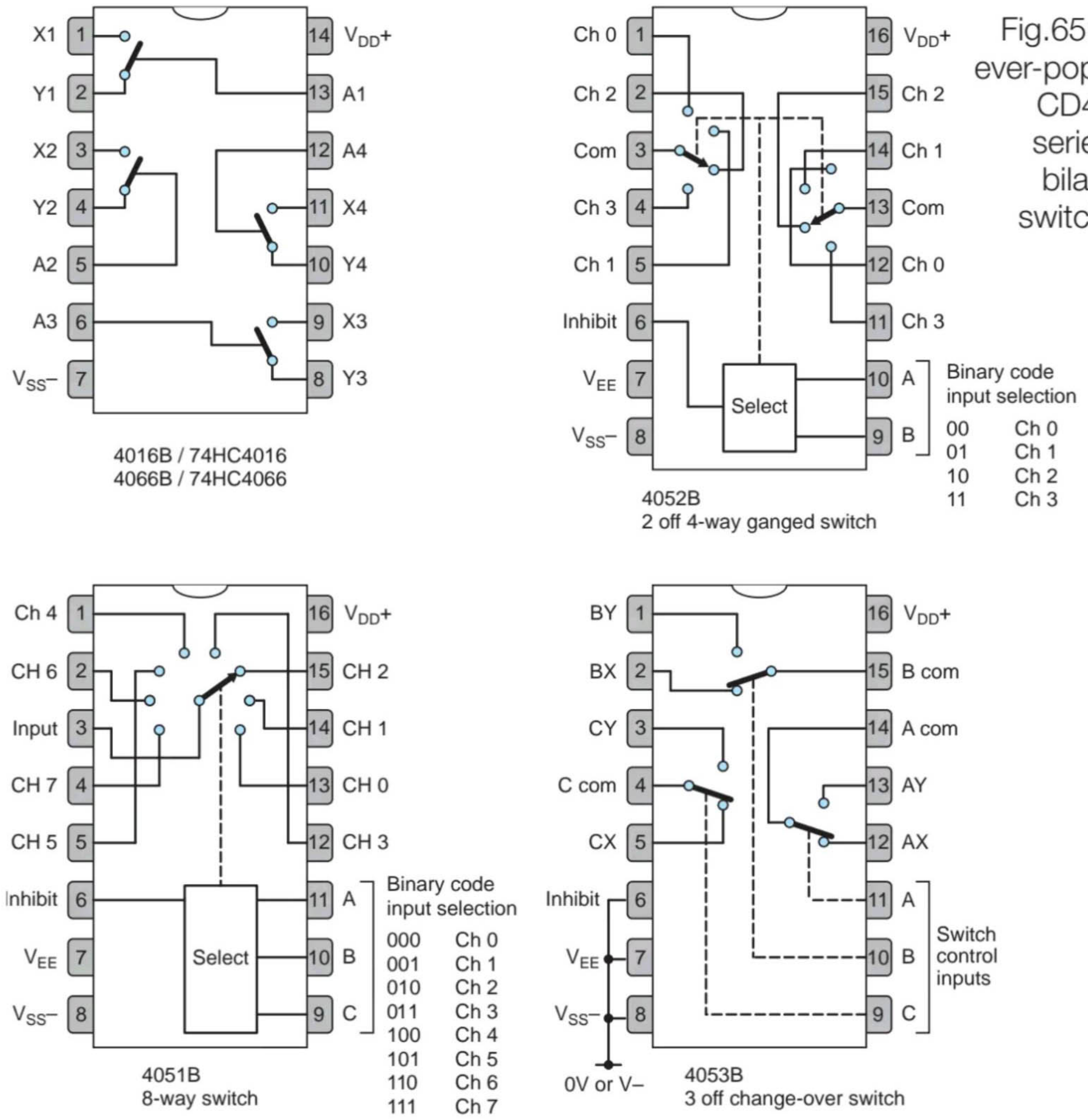

X1 1
Y1 2
X2 3
Y2 4
A2 5
A3 6
V_{SS}− 7
14 V_{DD}+
13 A1
12 A4
11 X4
10 Y4
9 X3
8 Y3
4016B / 74HC4016
4066B / 74HC4066
Ch 0 1
Ch 2 2
Com 3
Ch 3 4
Ch 1 5
Inhibit 6
V_{EE} 7
V_{SS}− 8
16 V_{DD}+
15 Ch 2
14 Ch 1
13 Com
12 Ch 0
11 Ch 3
10 A
9 B
Select
Binary code input selection
00 Ch 0
01 Ch 1
10 Ch 2
11 Ch 3
4052B
2 off 4-way ganged switch
Ch 4 1
CH 6 2
Input 3
CH 7 4
CH 5 5
Inhibit 6
V_{EE} 7
V_{SS}− 8
16 V_{DD}+
15 CH 2
14 CH 1
13 CH 0
12 CH 3
11 A
10 B
9 C
Select
Binary code input selection
000 Ch 0
001 Ch 1
010 Ch 2
011 Ch 3
100 Ch 4
101 Ch 5
110 Ch 6
111 Ch 7
4051B
8-way switch
BY 1
BX 2
CY 3
C com 4
CX 5
Inhibit 6
V_{EE} 7
V_{SS}− 8
16 V_{DD}+
15 B com
14 A com
13 AY
12 AX
11 A
10 B
9 C
Switch control inputs
0V or V−
4053B
3 off change-over switch

Fig.65: the ever-popular CD40xx series of bilateral switches.

VTL5C6
723 PRC
LED+

Fig.62: a Vactrol, an early type of electronic analog switch. Its control characteristic is proportional and linear enough for vibrato and tremolo circuits.

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* The International Union of Pure and Applied Chemistry (IUPAC) made "sulfur" the accepted spelling for element 16 in 1990; see https://pemag.au/link/abyg

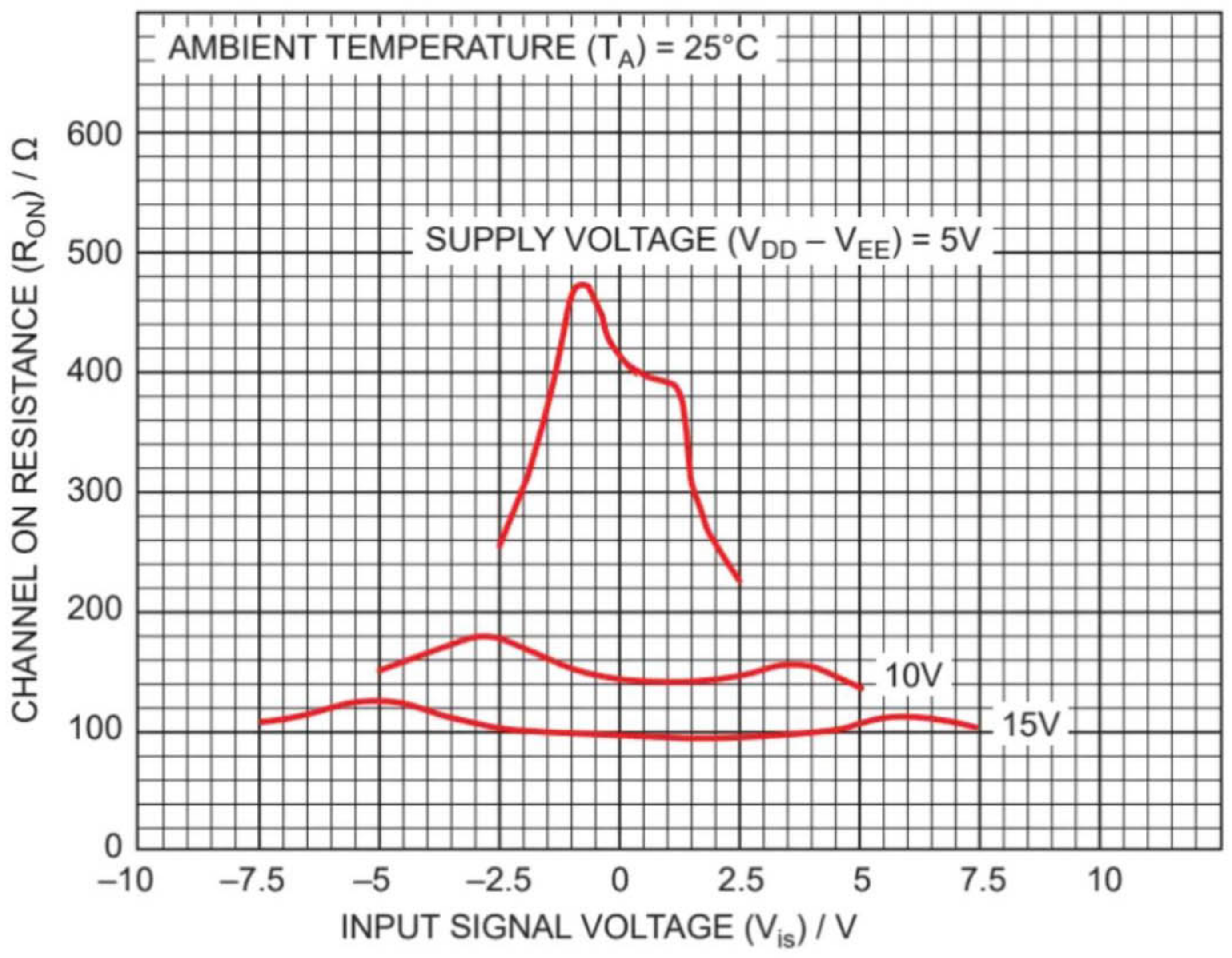


Fig.66: input voltage vs R_{ON} of a bilateral switch. This is the cause of the distortion. The resistance increases with lower supply voltage or higher temperature.

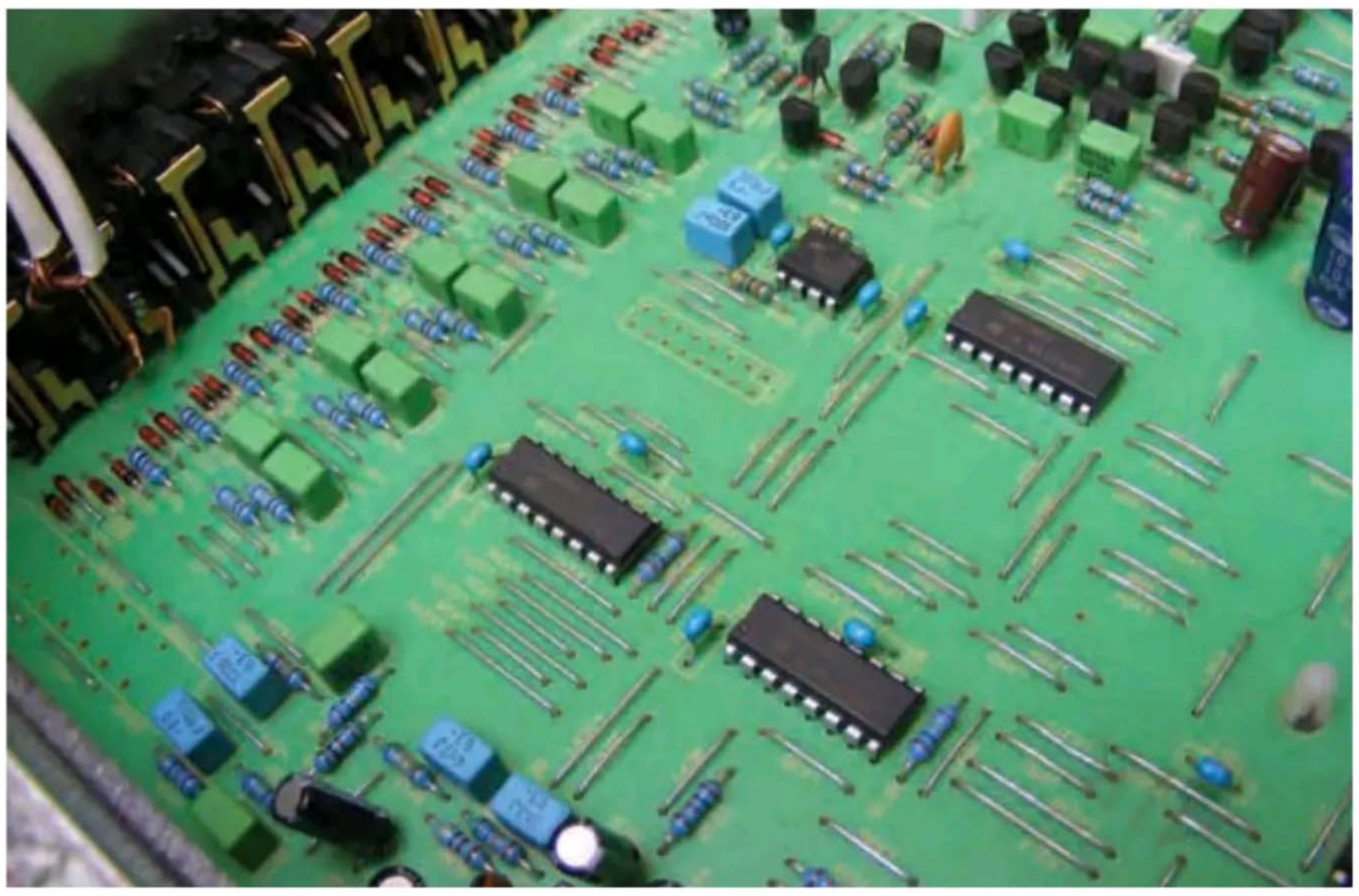


Fig.69: DG408 switch chips in the Arcam 65+. There were four; they must have got a special deal! Note the input protection diodes.

'bilateral topology' is shown in Fig.64. It cancels out some of the R_{ON} modulation.

It's possible to buy these in multi-stage ICs of the 4000 or 74HC series, containing complementary MOS or CMOS bilateral switches (introduced by RCA in the late 1970s). This is the cheapest approach, although they have a much higher R_{ON} than a discrete approach. Quad popularised these in their 34 preamp.

The most common types, the 4016 and the lower on-resistance 4066, give you four switches in a package, costing only around 50p. Other multi-pole devices include the 4051, 4052 and 4053, shown in Fig.65.

Unfortunately, these devices have the distinction of being the most unreliable small-signal semiconductors in the audio world. I suspect this is because the antistatic protection is compromised, being different for the linear devices than the logic devices. Always put them in sockets.

Another limitation is that the total power rail is 18V maximum, which causes a headroom loss when used with op amps, which have a total rail excursion of 36V. The R_{ON} modulation and hence distortion gets less as the power rail is increased, as shown in Fig.66. So always use at the highest voltage possible.

When using these ICs, I will often use ±8.2V zener-regulated rails with the op amps feeding them running at ±9.5V because their outputs can only swing to within 2V of the supply rails (rail-to-rail output op amps could use the same ±8.2V supply).

Note that, as with op amps, the signal needs to be biased to remain within the supply rails of the bilateral switches. If using a single-rail supply, that means biasing the signals to half-rail. For dual-rail supplies, the signals should be DC-biased to 0V.

The control voltage for the CD4016/66 is V+ for on and V– for off. The other chips, the 4051, 4052 & 4053 have internal level shifters, so they are controlled with normal logic levels, meaning logic low can be 0V instead of –7.5V. If an external level shifter is needed, you can use the configuration shown in Fig.67.

Voltage protection is usually needed when interfacing with op amps running on normal rails or the outside world. The Quad 34 used two back-to-back 6.8V zener diodes on its CD input.

The distortion was often in the region of 0.1% at a few volts peak-to-peak when used as straight substitutes for mechanical switches, like in the rudimentary circuit shown in Fig.68, much worse than the rest of the audio electronics. However, these devices were still a godsend for early 1980s mixer designers.

Some engineers, such as Steve Dove at Alice, developed circuits to make the distortion quite acceptable for broadcast mixers (more on that later). There are 74HC versions of the CD4016/66 chips; they have a lower maximum rail voltage of 10V but perform better at low voltages.

All these ICs work well in synthesisers, where I still use these devices. With all these switch chips, the FET gates are driven by internal fast logic, causing clicks from charge injection into the audio channel due to the gate capacitance.

Special chips, single 'sauce'

There are higher-specification MOS switching chips, such as Maxim/Vishay's DG408, used in the Arcam A65+ amplifier (see Fig.69). These are rated at 40V and give eight switches each. The catch is that the DG series is designed for fast analog multiplexing, a feature that is wasted for simple audio channel selection.

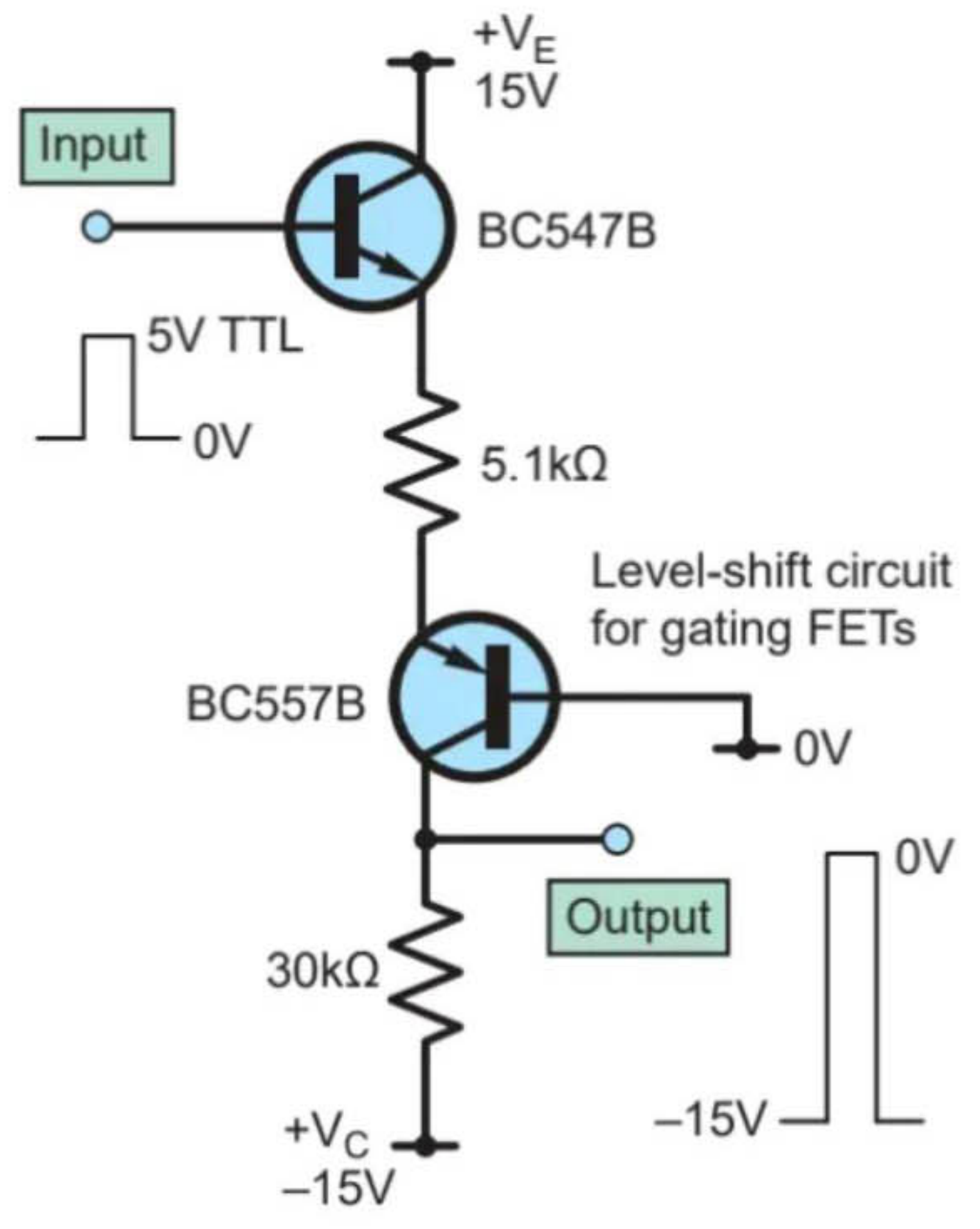


Fig.67: a level shifter for standard logic to control FET-based analog switches.

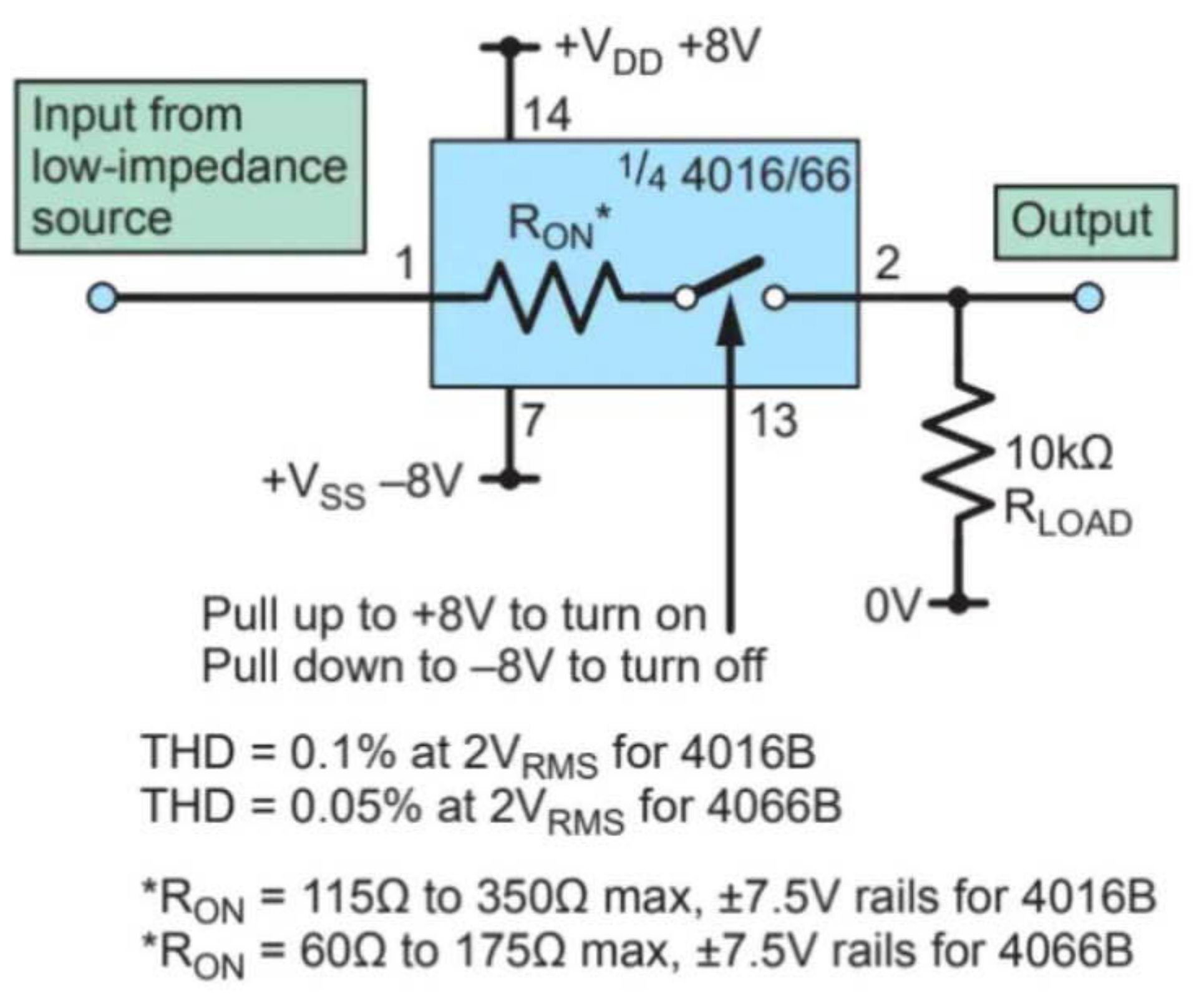

+V$_{DD}$ +8V
14
Input from
low-impedance
source
1/4 4016/66
R$_{ON}$*
1
2
Output
7
13
+V$_{SS}$ –8V
10kΩ
R$_{LOAD}$
0V
Pull up to +8V to turn on
Pull down to –8V to turn off
THD = 0.1% at 2V$_{RMS}$ for 4016B
THD = 0.05% at 2V$_{RMS}$ for 4066B
*R$_{ON}$ = 115Ω to 350Ω max, ±7.5V rails for 4016B
*R$_{ON}$ = 60Ω to 175Ω max, ±7.5V rails for 4066B

Fig.68: a 'data book' 4016 switch circuit. It works, but the distortion can be greatly improved with some tweaks.

ON
H11F1
809Q

Fig.70: an opto FET. These are useful where high isolation is required between the control and audio signals. I used one in a tone burst generator.

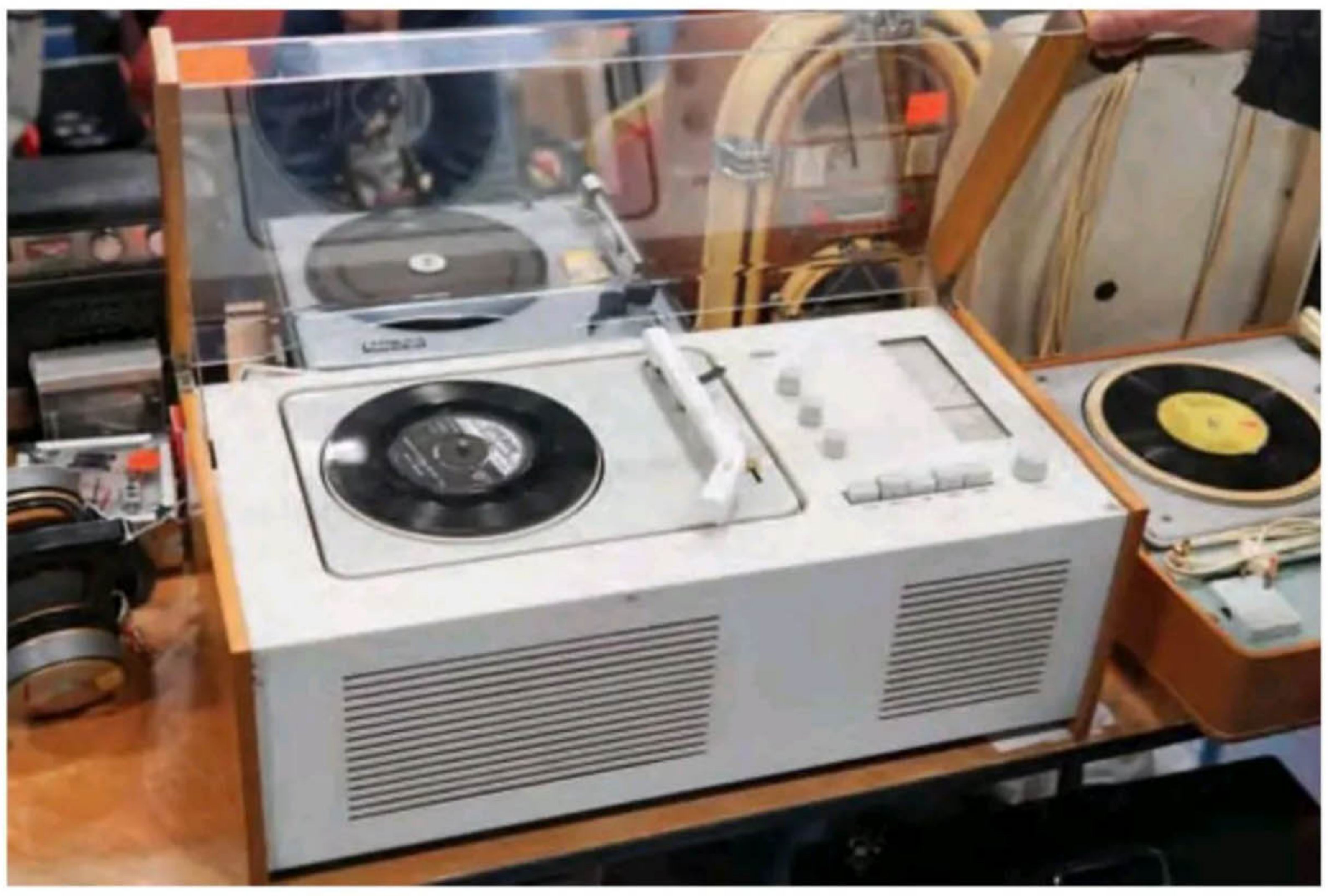


Fig.71: the Braun SK4 Phonosuper made interlocking push buttons trendy. They switched many things at the same time, resulting in a lot of electrical noise and mechanical clunks.

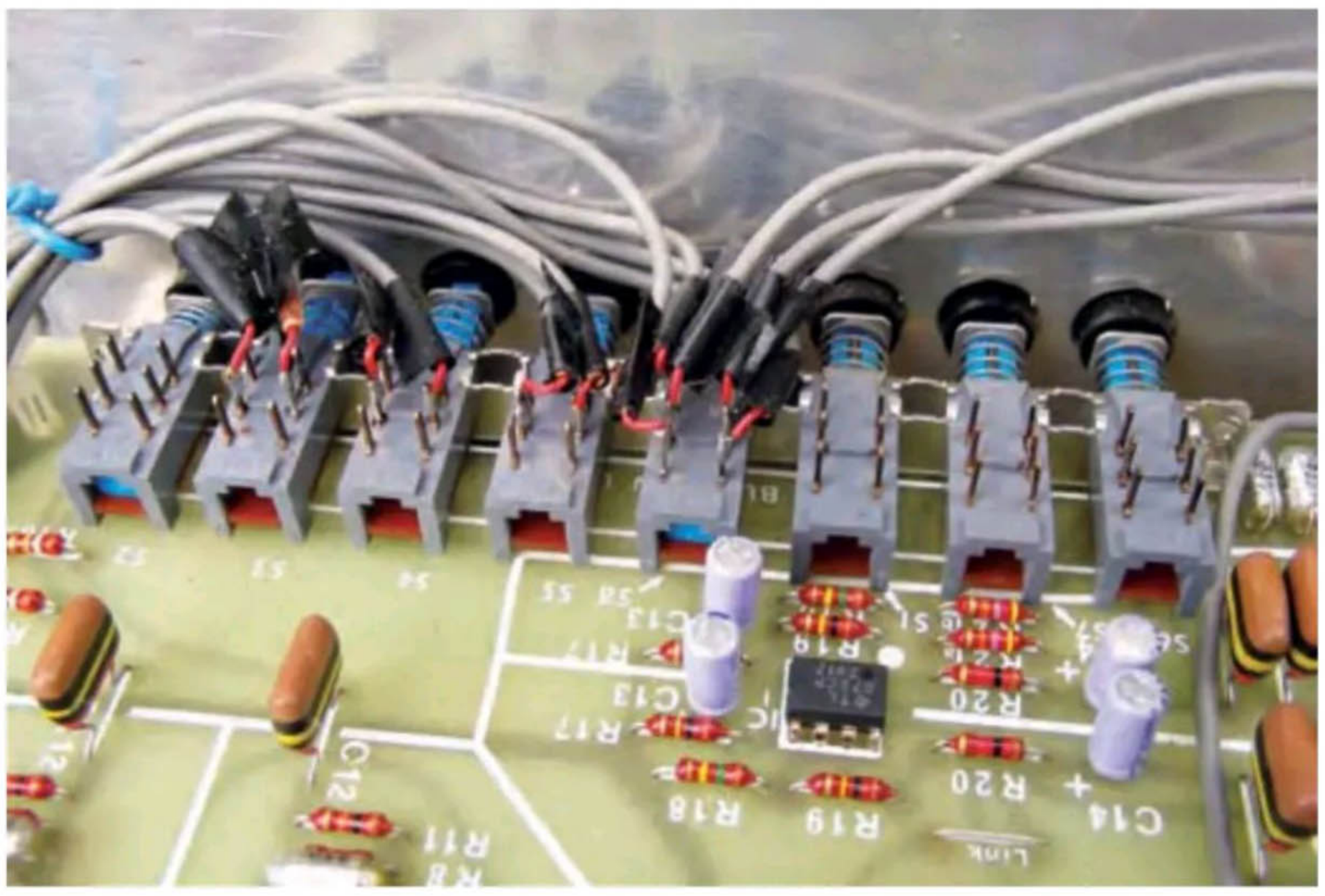


Fig.73: the wiring on the PW Winton has screened cables running from the sockets at the back to the front of the unit. Note the Alps interlocking switch assembly.

Another problem is that they cost almost £10 each when I last looked at Mouser. The distortion was not that good either, at around 0.04%. An excellent chip giving 0.003% was the hybrid bipolar/JFET SSM2412, alas now long deleted, a fate always befalling single-sourced audio chips. It even had internal ramping circuitry for clickless operation.

There is another dedicated chip from JRC (New Japan Radio Company), the NJM2750, a four-way input/output selector with 0.005% THD at 1V RMS. It's based on bipolar transconductance cells, and it's cheaper at £1.50 from Mouser. I await my samples for evaluation, which may be tricky to test since it's only available in surface-mount packages.

Discrete shopping

When using discrete FETs, it is possible to ramp the control inputs on the gates to reduce clicks to an inaudible low-level thump, even though there is the same amount of charge transfer.

It is even possible to get opto-FETs, a form of linear opto-isolator (Fig.70). They are free of control voltage breakthrough, but the H11F1M types I have exhibit a rather high on-resistance of 300Ω. The price is around £4 for a single switch.

If fast switching is needed, say for a tone burst generator, operation at the zero crossing is possible with electronic switching. This is another, more complex way of avoiding clicks, at least in theory.

However, subjectively, it doesn't work, as Studiomaster found when developing muting blocks for their mixer MIDI muting system. The audio signal is ramped up fast and still sounds like a click.

The result is that we are back to making discrete circuits using individual FETs for a top-quality Hi-Fi switch. MOSFETs such as the VN10 can be used, but they are asymmetrical, almost always have parasitic diodes (unless they are unusual four-lead types) and need static protection.

JFETs are a better choice and are symmetrical at audio frequencies, allowing the drain and source to be interchanged. Luckily, switching type JFETs such as the J112 and J175 are still cheap at around 35p each, unlike low-noise linear audio types.

We'll look at some practical electronic signal switcher circuits shortly, measuring the distortion and giving some useful multi-purpose PCBs to build.

Sent to Coventry

I visited Retrotech UK in Coventry on May 11th, an exhibition full of historic gear for sale. Here was the whole history of audio switching laid out before me. I was amazed to see a pristine Braun SK4, a true pushbutton pioneer, shown in Fig.71. However, at £450, it was too much, so I bought a £15 1979 Practical Wireless Winton instead, the first UK constructor's MOSFET amp (Fig.72).

This design shows one of the disadvantages of mechanical switching, with eight screened cables having to run to the front from the sockets at the back, as shown in Fig.73. Electronic switching allows the signal circuitry to all remain at the back, with only four unscreened DC control wires to be routed to the front. However, it was still a competent amp.

Quad 34 preamp circuit

Quad's design philosophy was to spend more money on the box and pots (shown in another Retrotech photo, Fig.74) while keeping the electronics cost effective. It ran Bi-FET TL071 op amps on low voltage rails of +8.6V and -9.4V for symmetrical clipping.

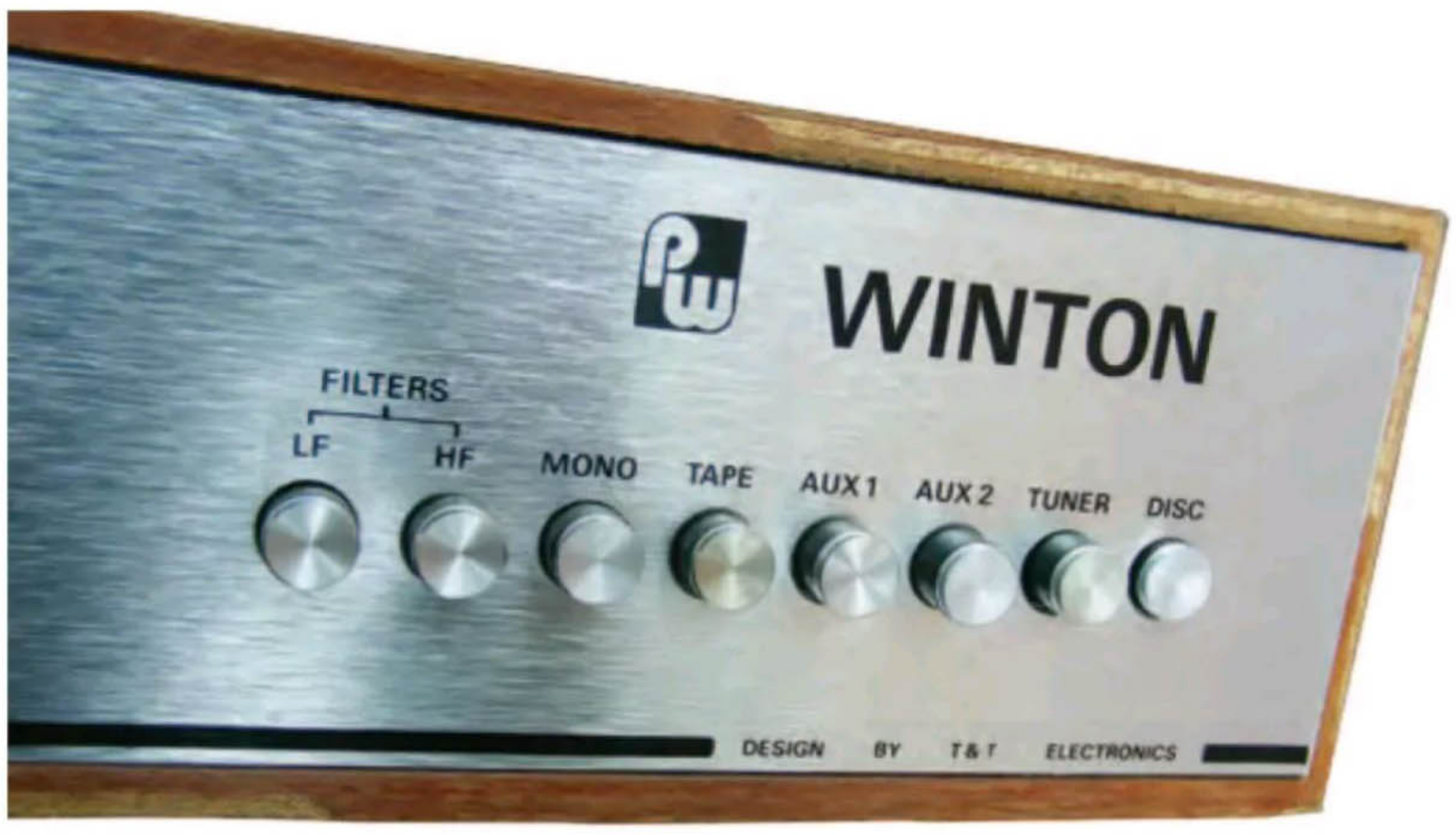


Fig.72: Practical Wireless' Winton amplifier with traditional clunky input selector switches. This was first the MOSFET output amplifier in a UK magazine, in 1979.

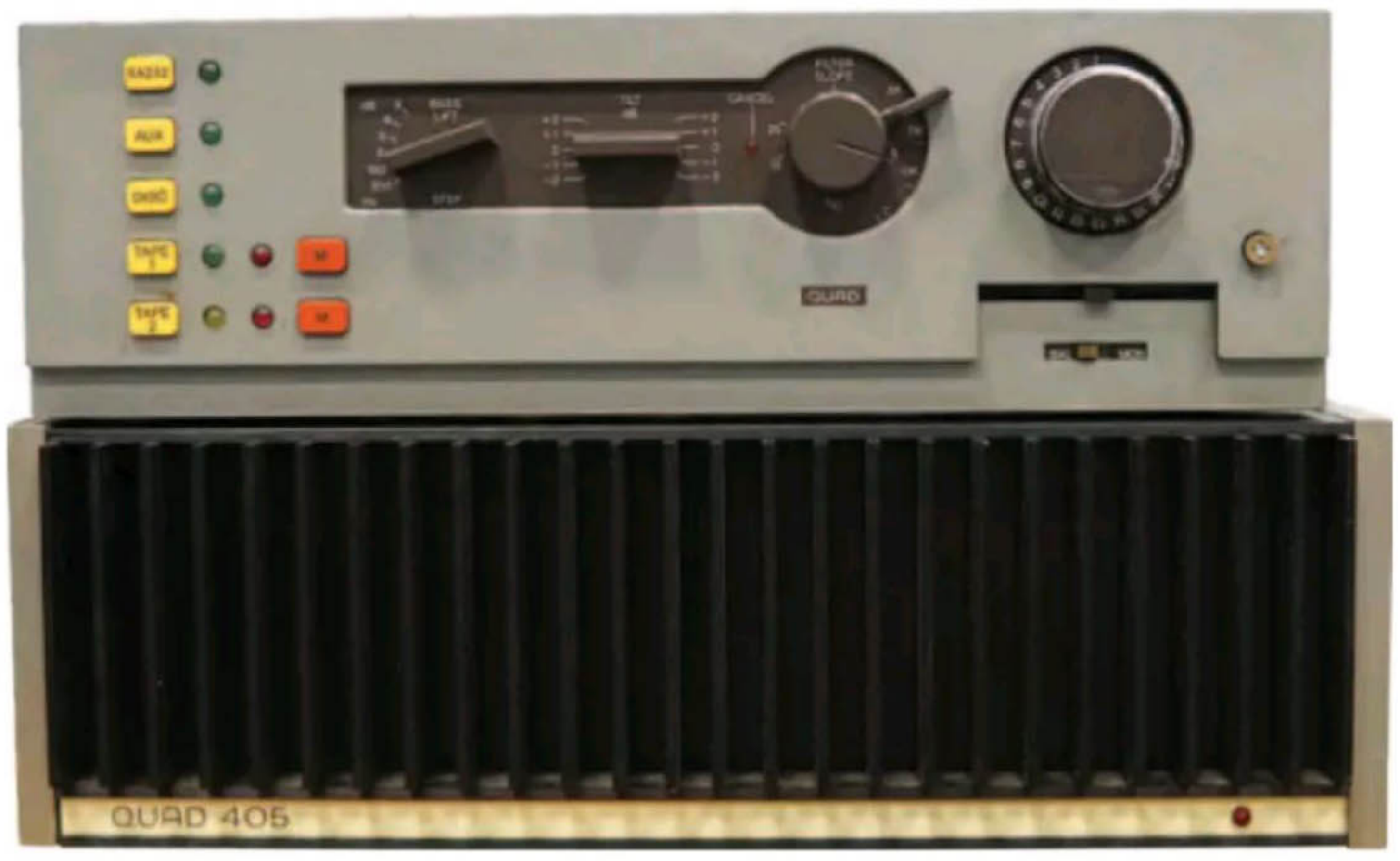


Fig.74: the epitome of middle-class classical elegance, the Quad 34 preamp and 405 power amp. This was the first successful design to use electronic input switching. It still works after 35 years and is priced at £500.

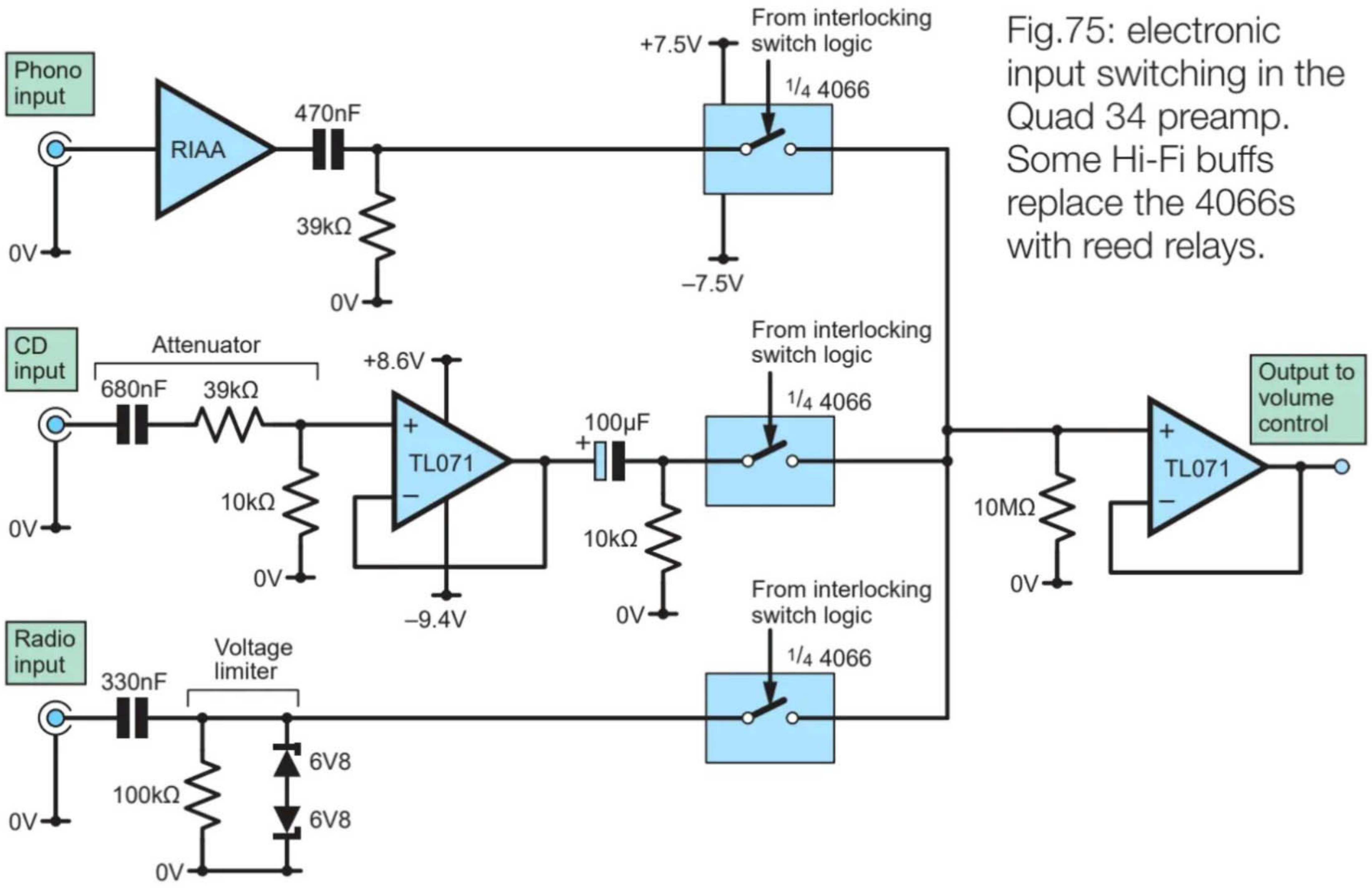

Phono input
RIAA
470nF
39kΩ
0V
+7.5V
From interlocking switch logic
1/4 4066
–7.5V
CD input
Attenuator
680nF
39kΩ
10kΩ
+8.6V
TL071
–9.4V
100µF
10kΩ
From interlocking switch logic
1/4 4066
Output to volume control
10MΩ
TL071
Radio input
Voltage limiter
330nF
100kΩ
6V8
6V8
From interlocking switch logic
1/4 4066

Fig.75: electronic input switching in the Quad 34 preamp. Some Hi-Fi buffs replace the 4066s with reed relays.

The switching was done with 4000-series logic and 4066 audio switches running at their maximum of ±7.5V. This gave a 6dB headroom penalty compared to circuitry using normal ±15V rails. This was overcome by placing an attenuator on the CD input to reduce the operating level.

The 4066 switching elements were wired in standard series mode, feeding an input impedance of 10MΩ, which was only possible because of the use of FET op amps. Clicks were minimised since there was no input bias current to worry about. The circuit of the input path is shown in Fig.75; the delicate 4066s are buffered from the outside world.

The subjective Hi-Fi fraternity didn't like the design, claiming this system had a sonic "MOSFET mist". I suspect there may have been prejudice against these devices because a DIY audio site states they were used in Plessey's System X telephone exchanges. I've found no primary source to corroborate this.

Quad's main designer and founder, Peter Walker, along with their consultant, Peter Baxandall, didn't design by ear but by maths and physics. This strategy didn't bother Quad's primary market, the classical-music-loving middle classes, with around 40,000 sold. Quad gear still turns up all the time, commanding high prices.

Improving CMOS switching circuits

The distortion caused by the variation in on-resistance (R_{ON}) with signal was minimised in the Quad circuit by loading it with a 10MΩ resistor (R6). This minimises the attenuation because of the resulting potential divider action. In turn, this makes the effect of variation of R_{ON} negligible.

In the RCA data book circuit, the load was 10kΩ, giving quite bad distortion, in the order of 0.4%. The Quad circuit reduced this to 0.004%.

Another way of minimising the effect of R_{ON} variation is to put the switching element into a virtual earth at the input of an inverting op amp circuit, as shown in Fig.76. This reduces the voltage across the switching element to very low levels. This depends on the value of the input resistor, R1. It is, as usual, a compromise between noise and distortion. A typical value is 10kΩ.

A possible disadvantage is that the circuit is inverting, although another inverting op amp stage can fix that.

A problem with the bilateral gates is that the break-over limit when off is ±7.5V. If a resistor is dropped to ground (like R3 in Fig.77), an attenuator is formed, limiting the voltage across the switch to half. There is a catch; the signal input current to the virtual earth is halved and the op amp has to make up for this, giving a noise gain of +6dB.

R3 can be replaced with two diodes connected in inverse parallel, avoiding the noise gain associated with the resistor. When the switch is on, the voltage on the virtual earth is so low the diodes do not conduct. When the switch is off, the diodes limit the signal, preventing breakover. This technique was used in old Neve modules, such as the BA714/5 filter modules. Interestingly, they used germanium AA142 diodes, but 1N4148s or Schottky types are fine.

Dual-switch circuits

All these circuits have quite poor off-state attenuation at high frequencies (10kHz), mainly due to internal capacitance across the series switching element. If the lower resistor is replaced by a shunt switching element with a control pin driven by an inverter, as shown in Fig.78, excellent attenuation is obtained while also solving the break-over problem.

Care must be taken that there is no possibility of both switches being on simultaneously, or the noise gain will be so high that a loud 'splat' will occur. Sometimes, a small gain-limiting resistor of around 100Ω (R4) is placed in series with the virtual earth pin as mitigation.

Complementary outputs are needed for the dual-switch circuit; one solution is the flip-flop circuit in Fig.59 (from last month). The finished Veroboard version is shown in Fig.79. The op amp

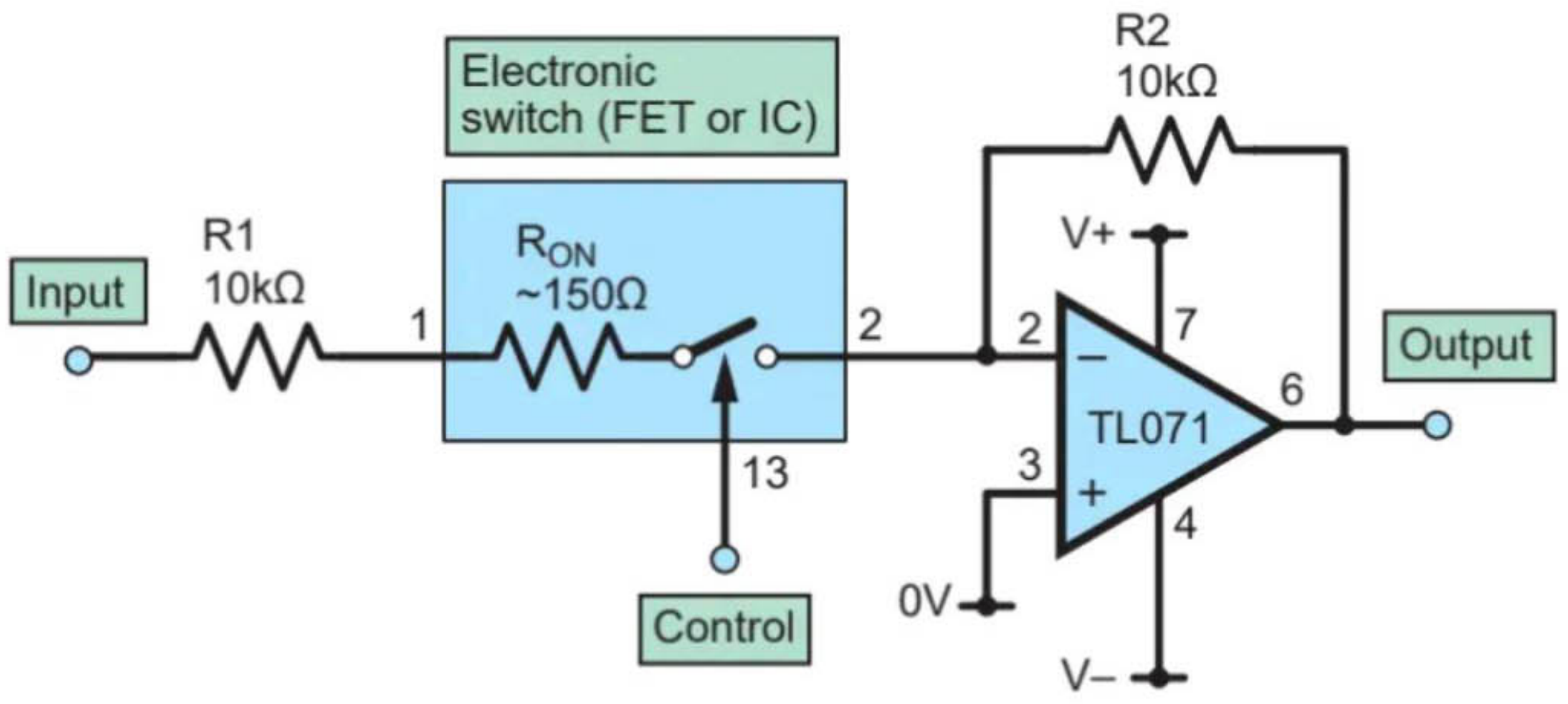

Electronic switch (FET or IC)
Input
R1
10kΩ
1
R_{ON}
~150Ω
2
13
Control
R2
10kΩ
V+
2
7
6
3
4
TL071
Output
0V
V–

Fig.76: using a virtual earth minimises the voltage across the switch when it is on, reducing distortion due to R_{ON} modulation.

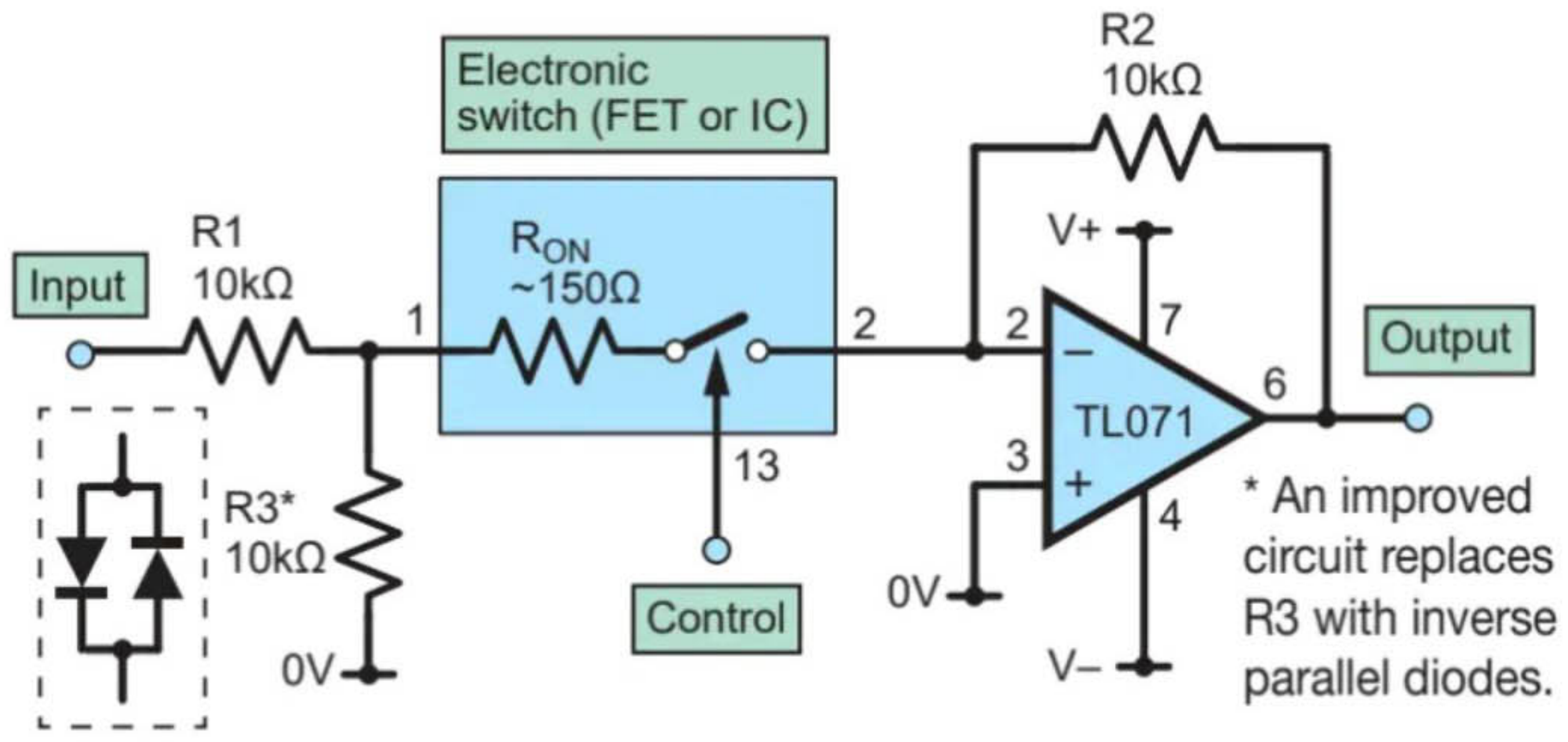

Electronic switch (FET or IC)
Input
R1
10kΩ
1
R_{ON}
~150Ω
2
13
R3*
10kΩ
0V
Control
R2
10kΩ
V+
2
7
6
3
4
TL071
Output
0V
V–
* An improved circuit replaces R3 with inverse parallel diodes.

Fig.77: break-over can be prevented when the switch is off by adding attenuation resistor R3, although the noise increases by 6dB.

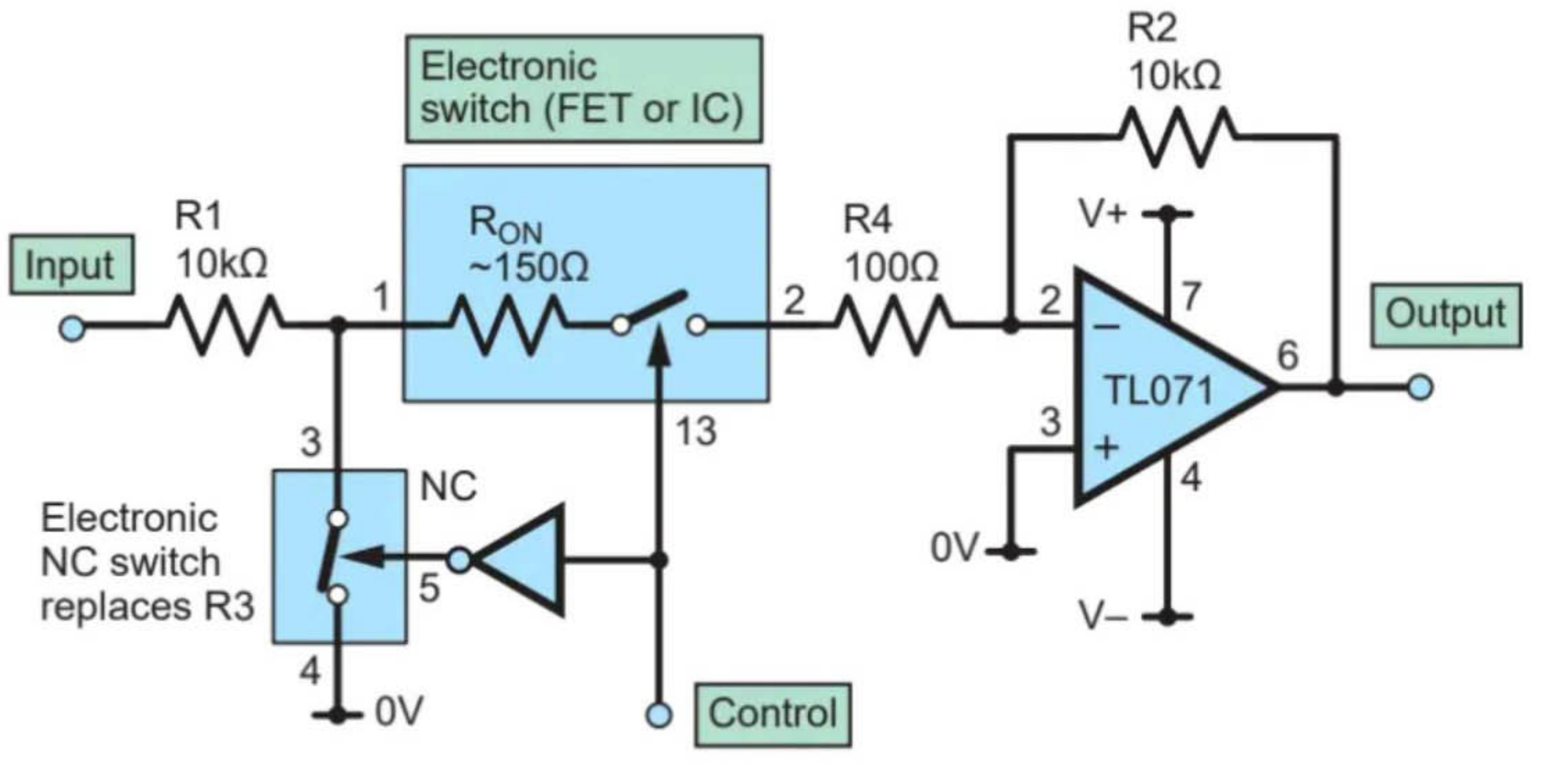

Electronic switch (FET or IC)
Input
R1
10kΩ
1
R_{ON}
~150Ω
2
13
R4
100Ω
3
NC
5
4
0V
Electronic NC switch replaces R3
Control
R2
10kΩ
V+
2
7
6
3
4
TL071
Output
0V
V–

Fig.78: adding a shorting switch element stops break-over and avoids noise gain (unless both are accidentally switched on simultaneously!).

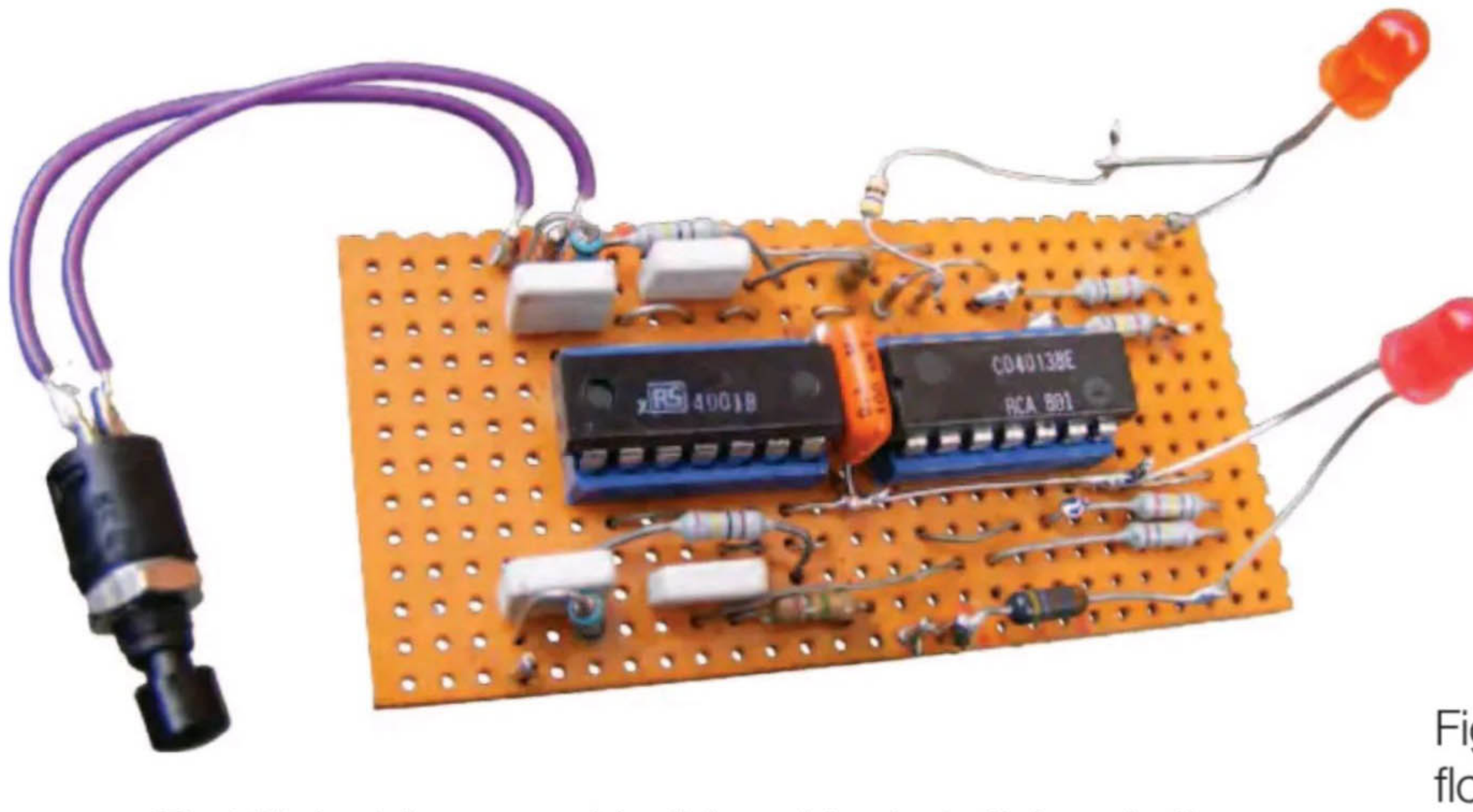


Fig.79: just to prove I build and test stuff, here's the over-engineered switch latching circuit from Fig.59.

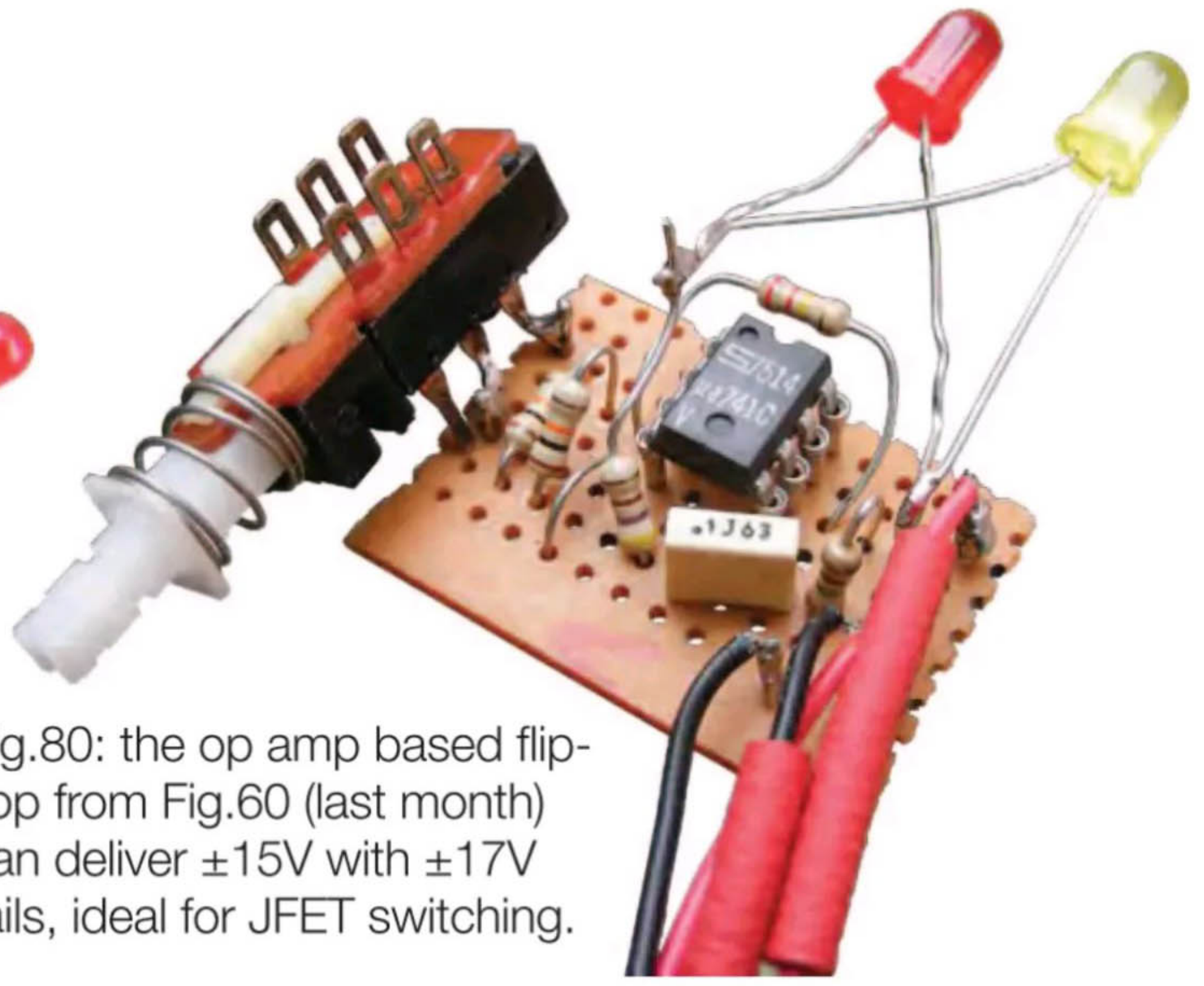


Fig.80: the op amp based flip-flop from Fig.60 (last month) can deliver ±15V with ±17V rails, ideal for JFET switching.

flip-flop circuit (Fig.60) will also work if the rails are reduced to suit. This is shown in Fig.80.

JFETs

All the above circuits can use discrete JFETs as the switching elements, with the advantages of no power rails being needed, higher headroom, greater reliability and less clicking noise. However, they often require high negative switching control voltages.

Normally, N-channel JFETs are used for switching because they are the cheapest, most readily available and have the lowest R_{ON}. Like all depletion-mode FETs, they require 0V to turn on and a large negative voltage to turn off, the pinch-off voltage or V_P. The low R_{ON} varieties require a higher voltage.

The most popular type is the J112, with the older TIS73 and U1898 occasionally encountered. These devices have an approximate R_{ON} of 50Ω. The V_P is typically -5V. A -15V control signal from op amp power rails will switch them off even with high-level audio going through them (which could subtract from the control voltage, causing break-over).

The J111 has a 30Ω R_{ON} but it might need -23V to switch off in the worst case, with a 10V RMS signal and V_P at the limit.

P-channel JFETs also switch on at 0V but need a positive voltage to turn off. This is more convenient, but their R_{ON} is higher. Only one type, the J175, is readily available and has an approximate R_{ON} of 80Ω (up to 125Ω in the worst case).

Boss effect in/out

The rudimentary circuit shown in Fig.81 works well for effects pedals where distortion does not matter much. This uses the 2SK30A JFET, which is popular with guitar pedal builders because it has a relatively low pinch-off voltage (V_P) of around -0.4V to -2V. This is needed because guitar pedals use 9V batteries, which drop to 6.5V as they discharge. The on-resistance is around 300Ω.

Mechanical 'stomp' switches are pretty unreliable, often suffering from latching and contact oxidation after a few years. An expensive way of preventing this is to use an Eaton EAT8943K32 switch from E. Preston Electrical Ltd, which has wiping contacts lasting 20 years. I use these in the most expensive Colorsound pedals.

The cheap way to do this is to go electronic with this circuit.

Bootstrapping

A neat trick for minimising the R_{ON} modulation in JFETs is to bootstrap the gate with the source voltage since the variation of the gate-source voltage (V_{GS}) modulates R_{ON}. A simple way of achieving this is to use a blocking diode and bootstrap resistor (22kΩ) joining the source to the gate, as in Fig.82.

This way, the audio rides on top of the control voltage. The diode also protects the gate from being forward-biased excessively and effectively holds V_{GS} at 0V for switch-on, even if +15V is applied. If the diode is grounded, the distortion is higher than if it is taken to a positive voltage since it is easier for the diode to become forward-biased.

22kΩ is typically a suitable value; the lower its value, the lower the distortion. It can sometimes be partially bypassed with a capacitor for lower HF distortion. The effect of the 22kΩ bootstrap was to lower the distortion from 0.003% to 0.0005% at 4V RMS when feeding a load impedance of 330kΩ.

Next month

That covers the basics of solid-state electronic switching of audio signals, but there are a lot of nuances, so we will have more on this topic next month. **PE**

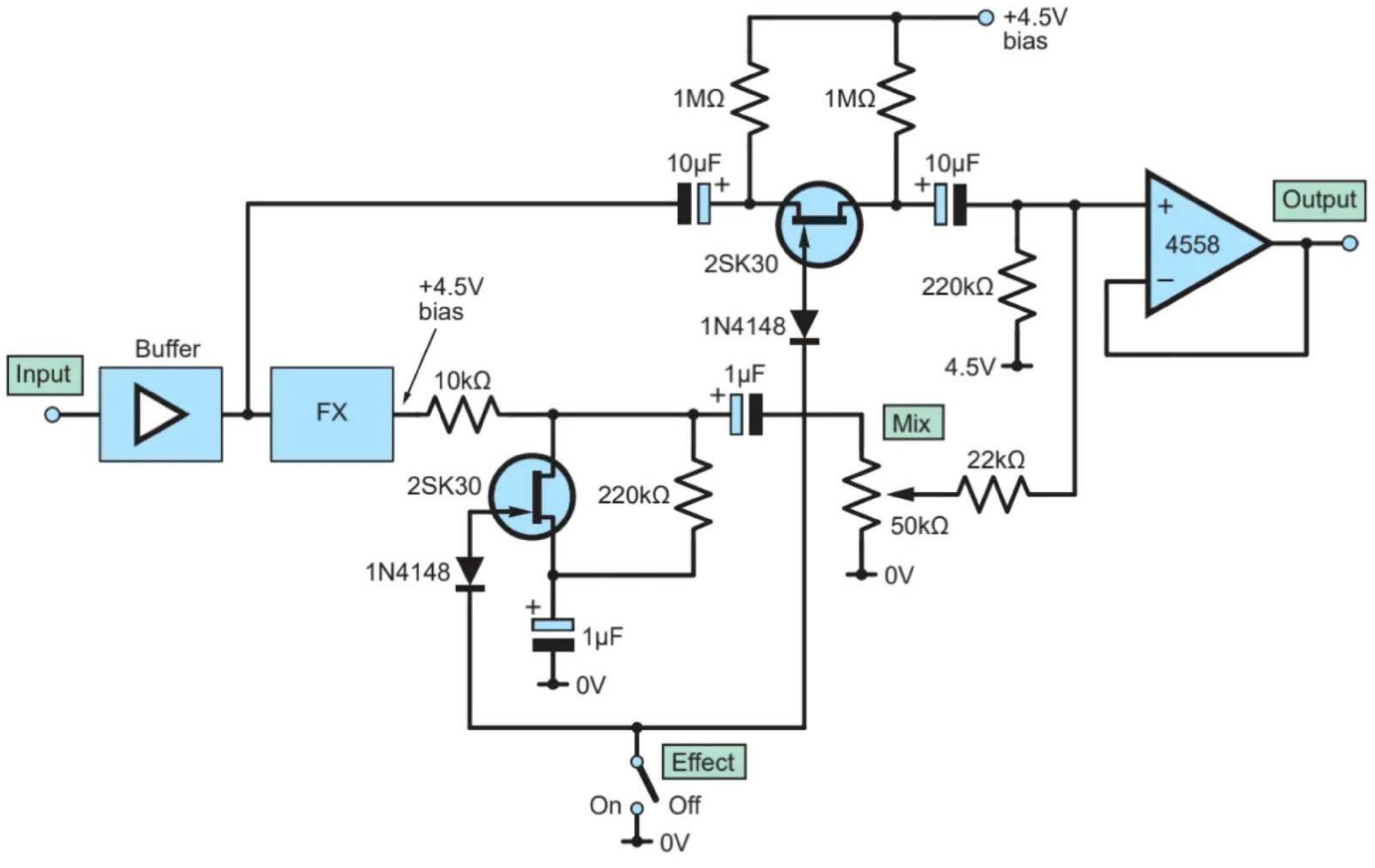
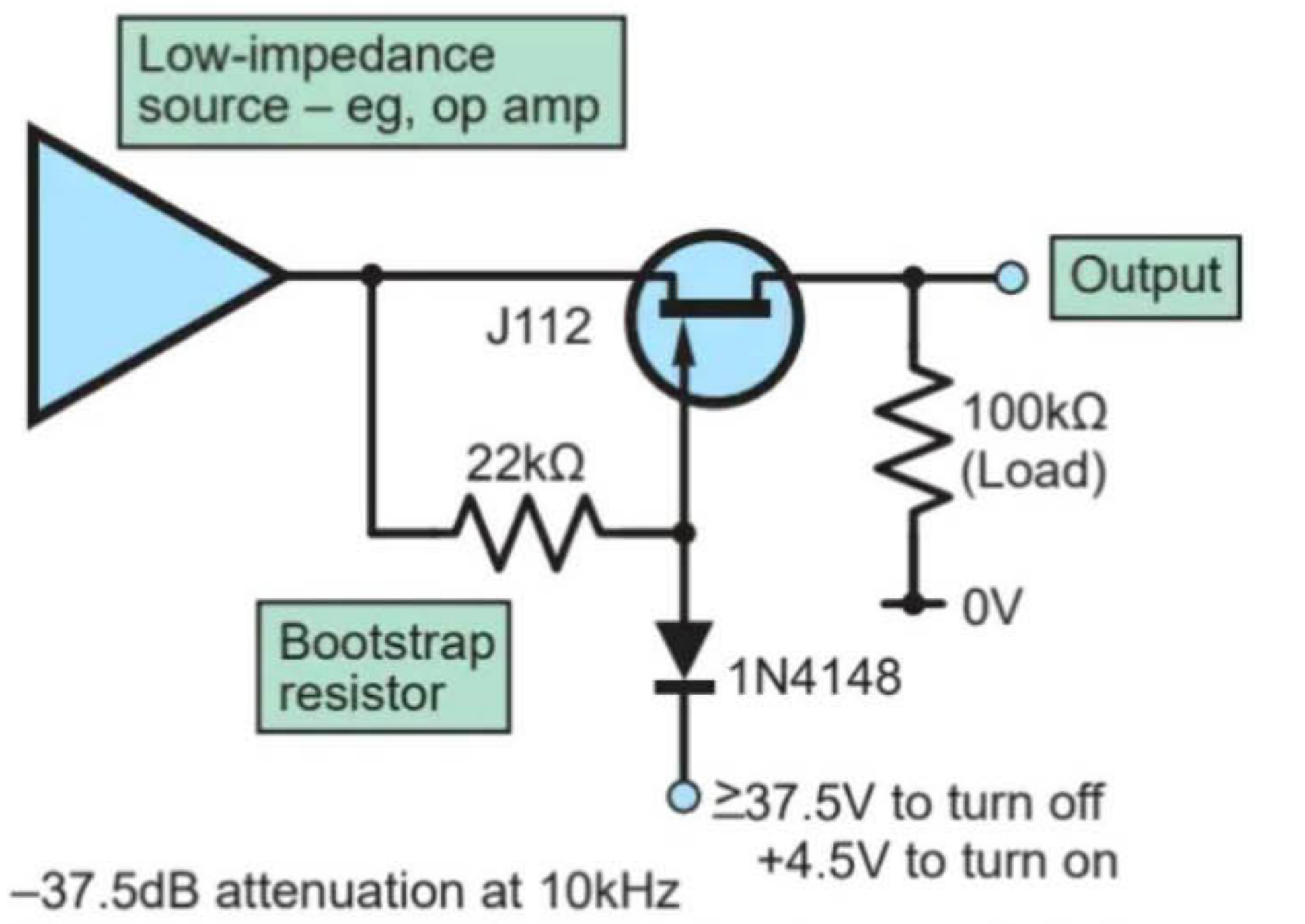


Fig.81: a rudimentary JFET effects in/out switching circuit from Boss guitar pedals. This was coupled to the discrete flip-flop in Fig.61 (again from last month). The 4.5V half-rail biasing enables the JFETs to switch off with their gates at to 0V.



–37.5dB attenuation at 10kHz
Distortion: 0.01%, $4V_{RMS}$ – no bootstrap and diode
Distortion: 0.0015%, $4V_{RMS}$ – with bootstrap and diode

Fig.82: bootstrapping the gate voltage with the audio signal reduces distortion.

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

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Note '10/63' denotes '10µF 63V'.

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Vigortronix 600Ω VTX-101-3001	£10
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Holco H2 2.2MΩ 1W, 1%	£1.00
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50kΩ A/log	£3.00
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Alps RK9 dual-gang 5kΩ RD law	£4.00
Alps 50k log tapped motorised stereo	£5.00
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Elysian Theremin (*EPE*, 1996)	£6
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Relays	
STC hermetic 4190 24V DPDT	£4.00
Switches Blore Edwards/Plessey	
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Elma 01 2-pole 6-way	£6.00
3PDT guitar pedal stomp switch	£2.50
Valves	
EC88, PCL84	£3.00

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 21 (common ground & BCD)

This is getting a little embarassing. For the past few columns, I've been promising that we were soon going to refresh our minds as to the concept of binary-coded decimal (BCD) and then investigate various deployments of BCD to 7-segment decoders in our evolving clock project. Unfortunately, every time we were poised to plunge into the BCD fray, something else popped up to divert our attention.

Well, believe it or not, the frabjous day has arrived. We are finally going to dip our toes into the BCD waters. I'm wearing my "I ❤ BCD" T-shirt and socks, so it must be true. In just a moment, we will truly turn our transient attentions to BCD, but first…

Up or down?

When we started using integrated circuits (ICs) to implement a 2:4 decoder (*PE*, July 2024), we ran across the problem of what to do with any unused inputs. Specifically, what to do with the four unused NOT (inverter) gates in our SN74LS04 IC.

We noted that there's a faint possibility an unconnected input, which may 'float' up or down, could potentially result in its gate undergoing uncontrolled oscillation, which would consume power and generate unwanted noise in the form of electromagnetic interference (EMI).

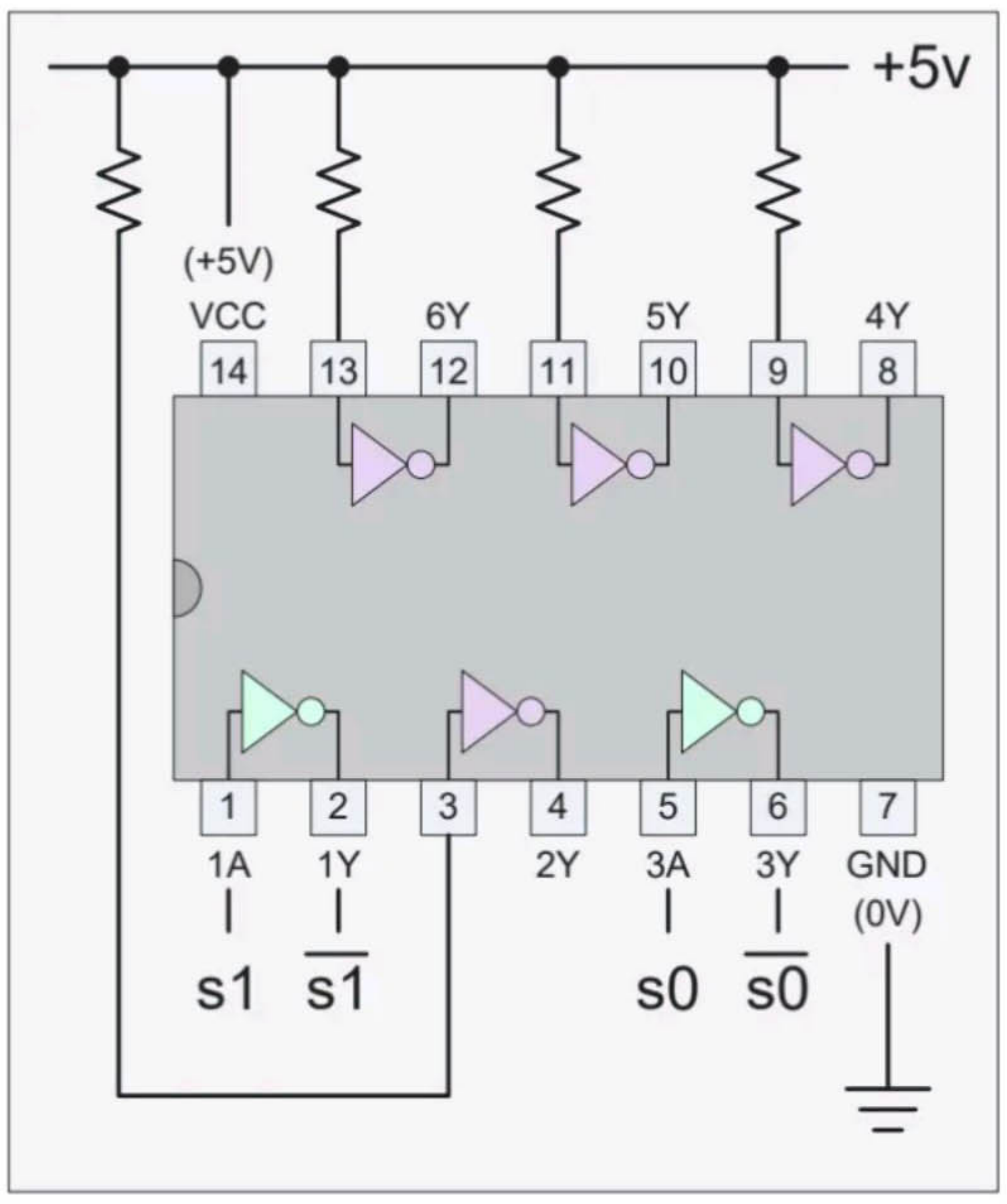


Fig.1: A better option for our unused inputs.

At that time, I mentioned that when logic gates are unused, as in our example, it's often left to the designer to decide whether to use pull-up or pull-down resistors and what their values should be. Things become more complicated in the case of partially used gates or functions, but that's a story for another day.

I suggested using 10kΩ *pull-down resistors*, and they would work perfectly well, but I subsequently received an email from Godfrey Manning, who hails from Greater London (amateur radio callsign G4GLM). Godfrey suggested that, in this case, *pull-up resistors* would have a slight advantage and would therefore be preferred.

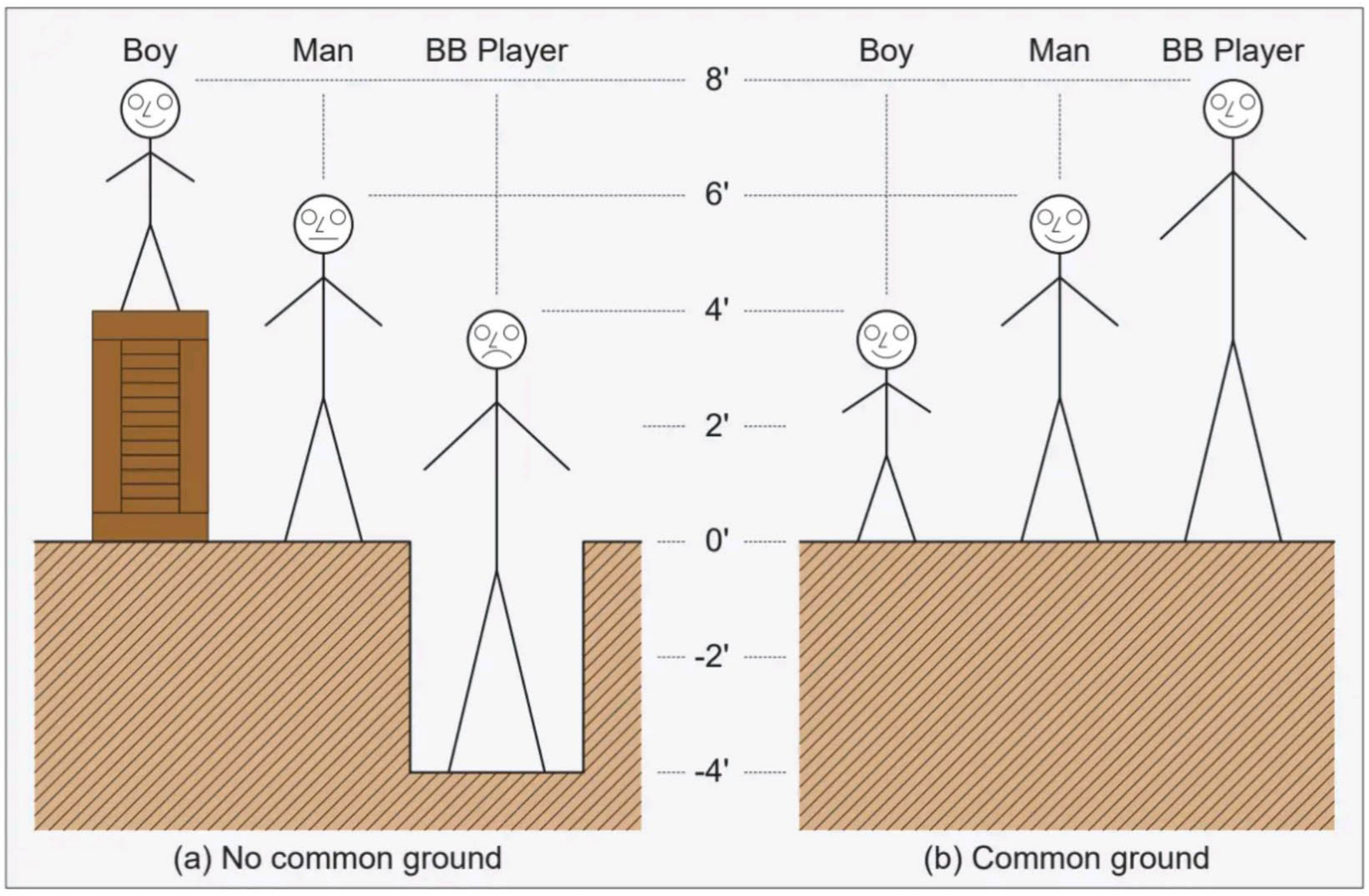
A cut-down version of Godfrey's message is as follows: "Dear Max, I'd like to be frank, only my parents insisted on Godfrey. TTL inputs are floating emitters (multiple emitters on the same transistor where a gate has more than one input). Unconnected, they are functionally logic high, although they won't read as such with a logic probe. To passivate a redundant gate, it's therefore best to connect the inputs to V_{CC} [+5V in our case], perhaps via a (value non-critical) pull-up resistor. This way, the gate draws minimal current."

Well, even though we are talking about minuscule amounts of current in this example, we are trying to follow best practices, so I've amended my circuit accordingly (Fig.1).

To be honest, the topic of pull-up and pull-down resistors could consume a complete column in its own right. For our purposes here, however, we can summarize things as follows:

1. For 74 (TTL), 74H (high-speed TTL), 74S (Schottky TTL) and 74LS (low-power Schottky TTL), use 1-10kΩ pull-ups or (less commonly used) pull-downs.
2. For 74AS (advanced Schottky TTL) and 74ALS (advanced low-power Schottky TTL), use 2-10kΩ pull-ups or (less commonly) pull-downs.
3. For 74F (fast TTL), use 1-4.7kΩ pull-ups or (less commonly) pull-downs.
4. For 74C (CMOS), 74HC (high-speed CMOS) and 74HCT (high-speed CMOS with TTL-compatible inputs), use 10-100kΩ pull-ups or pull-downs.
5. For CMOS 4000-series, use 10kΩ to 1MΩ pull-ups or pull-downs.

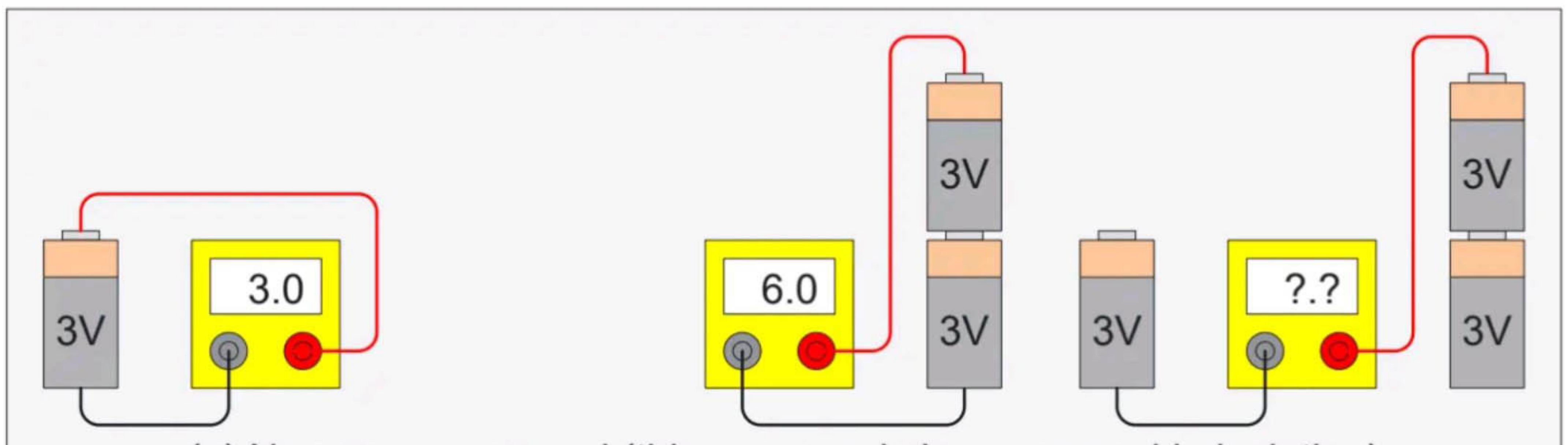
And now for the obligatory 'weasel words' (remember that eagles may soar, but weasels rarely get sucked into jet engines): "Always consult the data sheets for the specific components you are using." We are almost ready to hurl ourselves into the topic of BCD, but first…



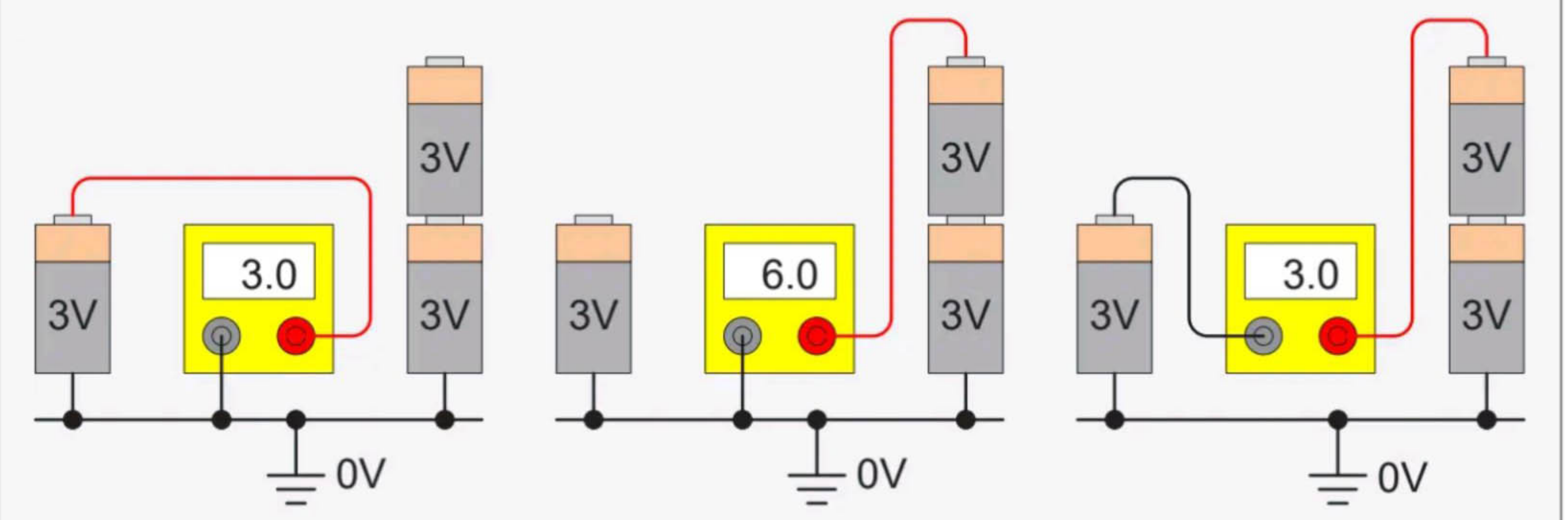
(a) No common ground

(b) Common ground

Fig.2: This shows one reason why having a common ground is important (there are others).



(a) No common ground (things can only be measured in isolation)



(b) Common ground (things can be measured in relation to each other)

Fig.3: A common ground allows things to be measured in relation to each other.

Finding common ground

As part of the debugging exercise in our previous column (*PE*, August 2024), we created a set of six logic probes on a half-size breadboard. Although I showed the power and ground wires feeding our probe board as coming from our other breadboards, I mentioned that we could use a separate +5V supply if we wished. I also noted that all the breadboards and power supplies must share (be connected to) the same ground.

You may have run across something like this before. It's not unusual to see a project where a 5V Arduino Uno is being used in conjunction with a 12V servo motor controller, for example. In this case, there will typically be two separate power supplies whose grounds are connected. Have you ever wondered why? Well, make yourself comfy and I shall expound, explicate, and elucidate (I can do all three with one hand tied behind my back while chewing gum!).

Let's start with an analogy. Suppose we have a 4-foot (122cm) tall boy, a 6-foot (183cm) tall man and an 8-foot (244cm) tall basketball player, all standing next to each other and all looking in the same direction. Who will be able to see the farthest? If your knee-jerk reaction is to respond, "the basketball player, of course", then you've fallen into my cunning trap.

Although I stated that our three characters are standing next to each other, I failed to mention that the boy is perched on a 4-foot tall box, while the basketball player has been plunged into a 4-foot deep hole (Fig.2a). The point is that my question is meaningless unless everyone involved is standing on (ie, measured in relation to) a common ground (Fig.2b).

Keeping this analogy in mind, suppose we have a 3V battery on its own and another two 3V batteries connected in series to give a 6V source. Without instituting a common ground, things can only be measured in isolation (Fig.3a). By comparison, once a common ground has been established, they can be measured in relation to each other (Fig.3b).

Of course, it's not simply a case of measuring things. Having a common ground is a requirement for circuits involving multiple voltage sources to perform their magic, but we don't need to discuss this any further here.

I don't know about you, but I'm quivering in anticipation, poised to plunge into the invigorating BCD waters, but first…

2 = 10

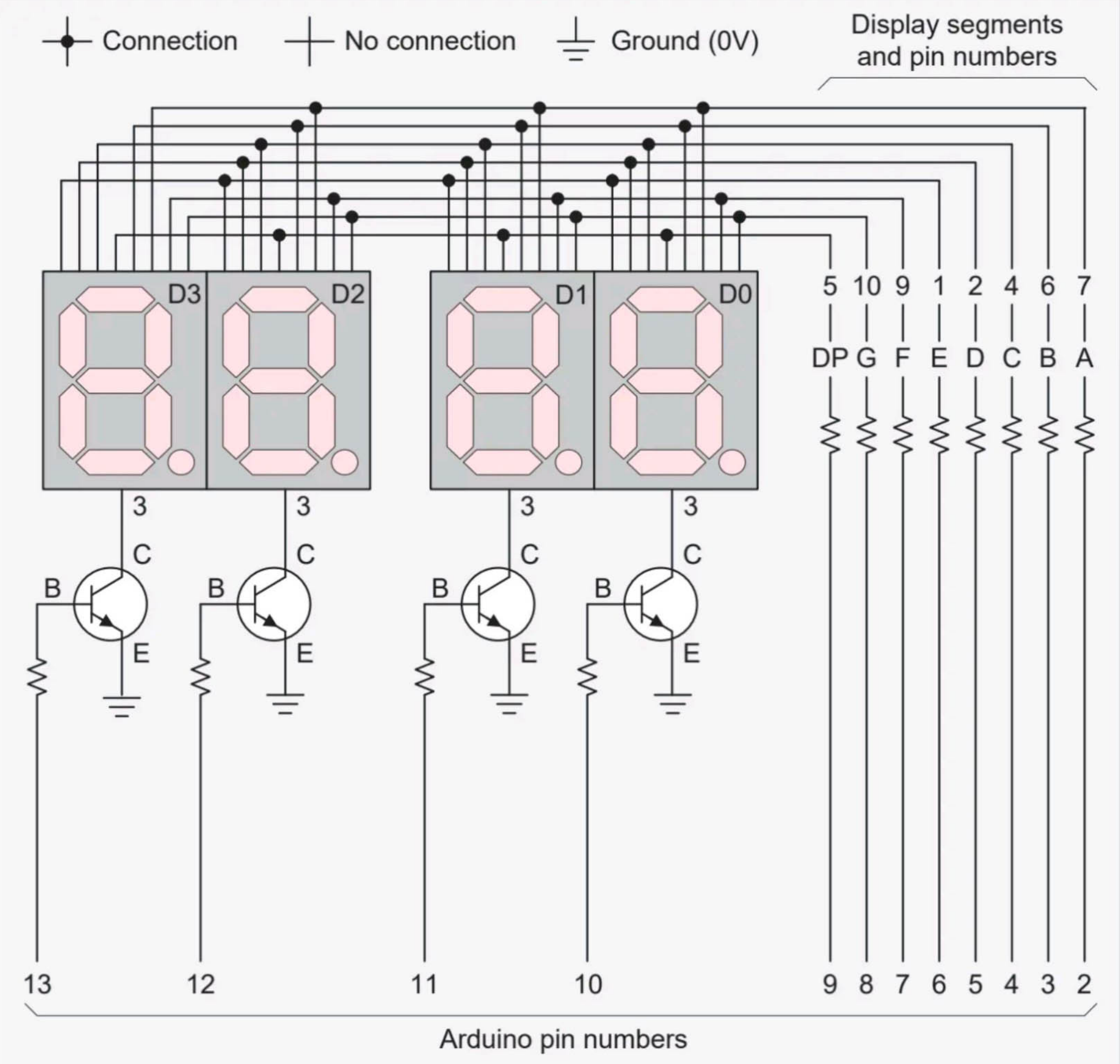
When you saw the heading, did you think, "Ah, I know this one. Max means that 10 in binary is 2 in decimal"? If so, then (a) I'm impressed that you've been paying attention and (b) you're wrong (I'm afraid I'm being a little tricky today).

To remind ourselves about the status of our clock project, we are currently controlling four 7-segment light-emitting diode (LED) displays. Also, we are restricting ourselves to using only 12 of the digital input/output (I/O) pins on our Arduino Uno.

Although the Uno has 14 digital I/Os, numbered 0 to 13, pins 0 and 1 are reserved for communications with the host computer. Ideally, we want to keep as many of these I/Os as possible free to implement additional functionality in the future.

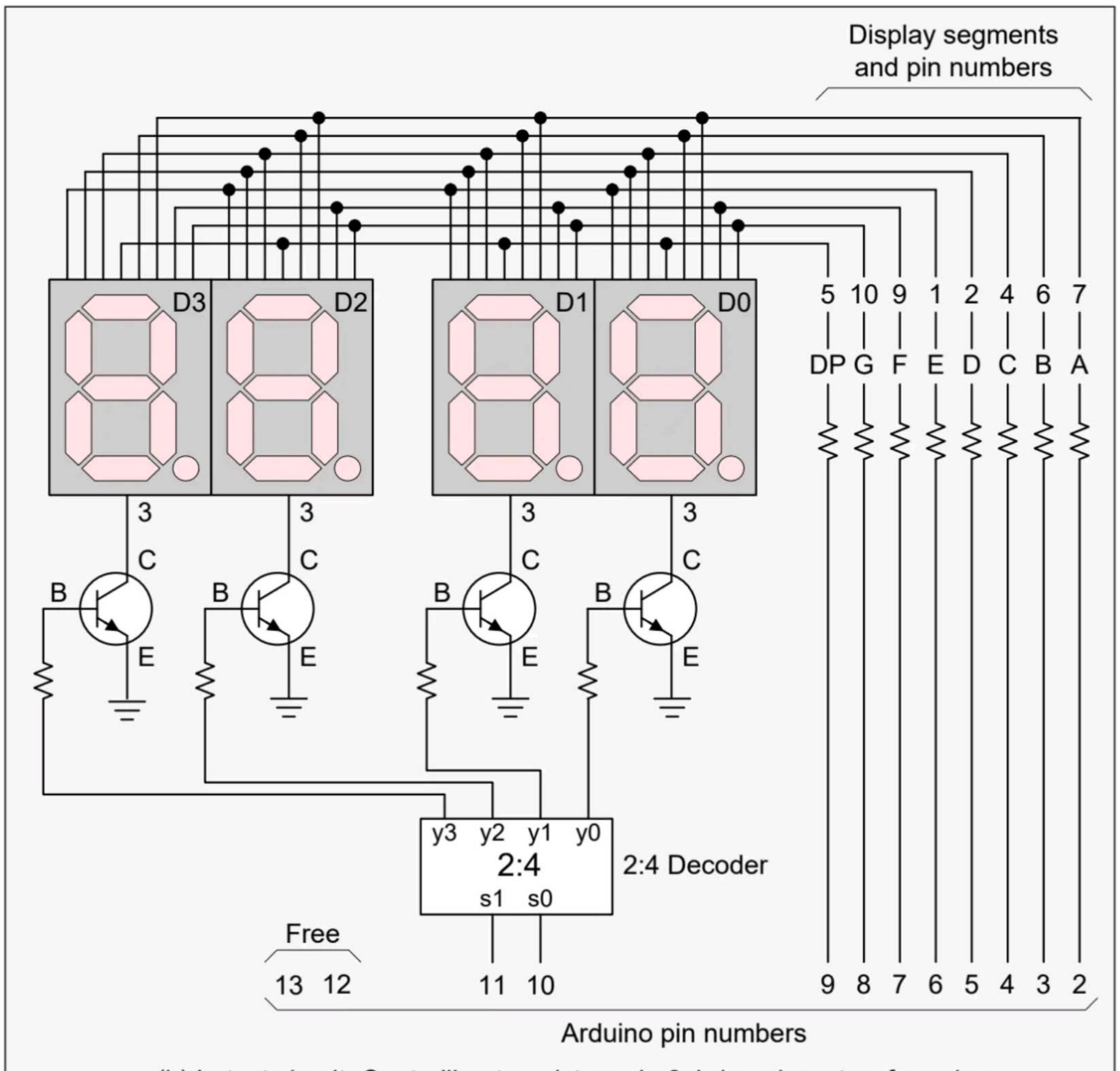
Remembering that our 7-segment displays really have eight segments (seven to represent numerical and other characters, plus one for the decimal point), our original circuit employed eight of our Arduino's pins to drive the displays in parallel (side-by-side).

We used the remaining four pins to directly control four transistors, each of which can activate or deactivate its corresponding display (Fig.4a). The idea



(a) Original circuit: Controlling transistors directly = no free pins.

Fig.4a: The clock display circuit without a decoder needs 12 pins to drive it.



(b) Latest circuit: Controlling transistors via 2:4 decoder = two free pins.

Fig.4b: Using a 2-to-4 decoder reduces the number of pins required to 10.

is to multiplex our displays, having only one active at a time, but switching them on and off so quickly that our eyes and brains are fooled into perceiving them as all being active all the time.

Now, cast your mind back to when we decided to employ a 2:4 decoder to control our transistors (*PE*, July 2024), shown in Fig.4b. We are using two of the Arduino's digital I/Os to drive the inputs to the decoder. These inputs can be presented with four binary patterns: 00, 01, 10 and 11.

Our decoder uses these patterns to place one of its four outputs in its active state (which is logic 1, in our case). The reason for using this decoder is that it frees up two of our digital I/Os.

At that time, we noted that if we ever decide we want to drive five to eight displays, we would have to switch to a 3:8 decoder (with three inputs and eight outputs). That would leave us with only one free pin.

Similarly, if we needed to drive nine to 16 displays, we would have to employ a 4:16 decoder (with four inputs and sixteen outputs). That would leave us with no free pins.

Purely for the sake of an example, suppose we wished to control ten displays. Although using a 4:16 decoder may be better than being poked in the eye with a sharp stick, it still leaves something to be desired. Is there a better way?

Well, hold onto your hat because I'm about to blow your socks off (I can't help myself; I'm infatuated with idioms). I know how to control ten displays using just two pins with only a slight variation on our existing circuit (hence the "2 = 10" heading). I'll tell you about this technique in a moment, but first…

Combinatorial vs sequential

Thus far in our experiments, except for the internals of the Arduino itself, we've employed only 'combinatorial logic'. This refers to logic functions constructed using primitive logic gates (NOT, AND, OR, NAND, NOR etc). They produce an output or outputs from the *combination* of one or more input but have no memory of anything that has gone before.

It's also possible to use primitive gates to create 'sequential logic'. This refers to logic functions that remember the past. That is, functions that produce an output or outputs with value(s) that depend both on the present values of their input signals and on the *sequence* of past inputs.

For example, a "flip-flop" is a logic function with two stable states (0 and 1) that can be used to store one bit of binary data. There are a variety of different flip-flop implementations. One common type is called a D-type flip-flop. The symbol and truth table for a D-type flip-flop are shown in Fig.5.

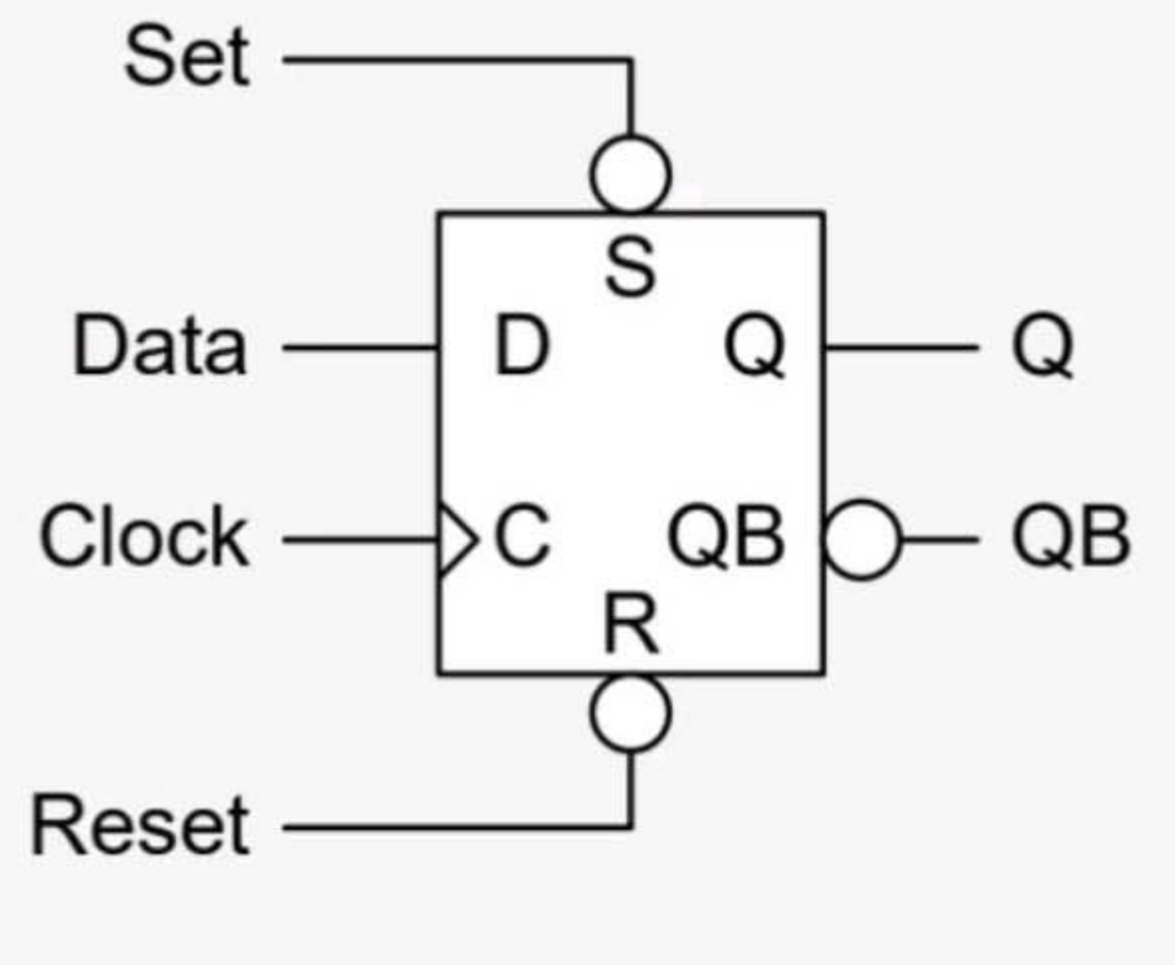
I know this appears a bit complicated at first glance, but it's not as bad as you might fear. As always, let's take things step by step, starting with the fact that this type of function can be created with just a handful of the primitive logic gates we've discussed before.

The small circles (called 'bubbles' or 'bobbles') on the symbol indicate active-low inputs (`S` and `R`) or outputs (`QB`). In the case of the outputs, `Q` is known as the 'true' output and `QB` is known as the 'complementary' output. This is because `QB` has the opposite or complementary logical value to `Q`.

The `(n)` and `(n+)` annotations associated with the outputs in the truth table represent time. In this case, `(n)` indicates 'now' or whatever the value is currently, while `(n+)` indicates 'now plus' or what the value is going to become.

In this example, our `S` (Set) and `R` (Reset) inputs are both active-low (active-high versions are also available). Also, as we will discuss, the truth table tells us these are both asynchronous, which means they aren't synchronised to (they act independently from) the clock (synchronous versions are also available). Some flip-flips have only an `S` input, others have only an `R` input, and some don't have either.

We know the `C` (Clock) input is edge-triggered because this is indicated by the '>' in the symbol. Furthermore, the lack of a bobble on this input indicates that this is a positive-edge clock (ie, it performs its magic on a 0-to-1 or 'rising' transition). If a bobble were present, that would indicate a negative-edge



Inputs				Outputs		Mode
S	R	C	D	$Q_{(n+)}$	$QB_{(n+)}$	
0	1	X	X	1	0	Set (Q → 1)
1	0	X	X	0	1	Reset (Q → 0)
0	0	X	X	?	?	Not allowed
1	1	↑	0	0	1	Load data
1	1	↑	1	1	0	Load data
1	1	↓	X	$Q_{(n)}$	$QB_{(n)}$	Memory

Fig.5: The configuration of a typical D-type flip-flop with its logic table.

clock (ie, it would perform its magic on a 1-to-0 or 'falling' transition).

The ↑ and ↓ characters in the truth table indicate rising (0-to-1) and falling (1-to-0) transitions, respectively. Finally, `X` characters in the truth table represent 'don't care' values, while `?` characters indicate 'don't know' values.

Putting all of this together, the first row in this truth table tells us that when we have an active 0 on the `S` input (and an inactive 1 on the `R` input), we don't care what's on the `C` or `D` inputs because the `Q` output will be set to 1 and the `QB` output will assume the complementary 0 value.

The next row tells us that when we have an active 0 on the `R` input (and an inactive 1 on the `S` input), we don't care what's on the `C` or `D` inputs because the `Q` output will be reset to 0 and the `QB` output will assume the complementary 1 value.

The next row tells us that it's illegal for both the `S` and `R` inputs to be in their active states at the same time. If this were to occur, we wouldn't know what values to expect on the `Q` and `QB` outputs.

Assuming that both `S` and `R` are in their inactive 1 states, a ↑ rising edge on the `C` input will load whatever value is on the `D` input into the flip-flop causing it to appear on the `Q` output (and the `QB` output will assume the complementary value). Subsequently, a 1, 0 or ↓ falling edge on the `C` input will leave the `Q` and `QB` outputs unchanged.

Phew, I didn't realize this was going to take so long to explain. If you wish to learn more about how we use primitive logic gates to construct functions like our D-type flip-flop, then you will find this topic is covered in ~~excruciating~~ exhilarating detail in my book *Bebop to the Boolean Boogie* (**https://bit.ly/4a6wDDm**).

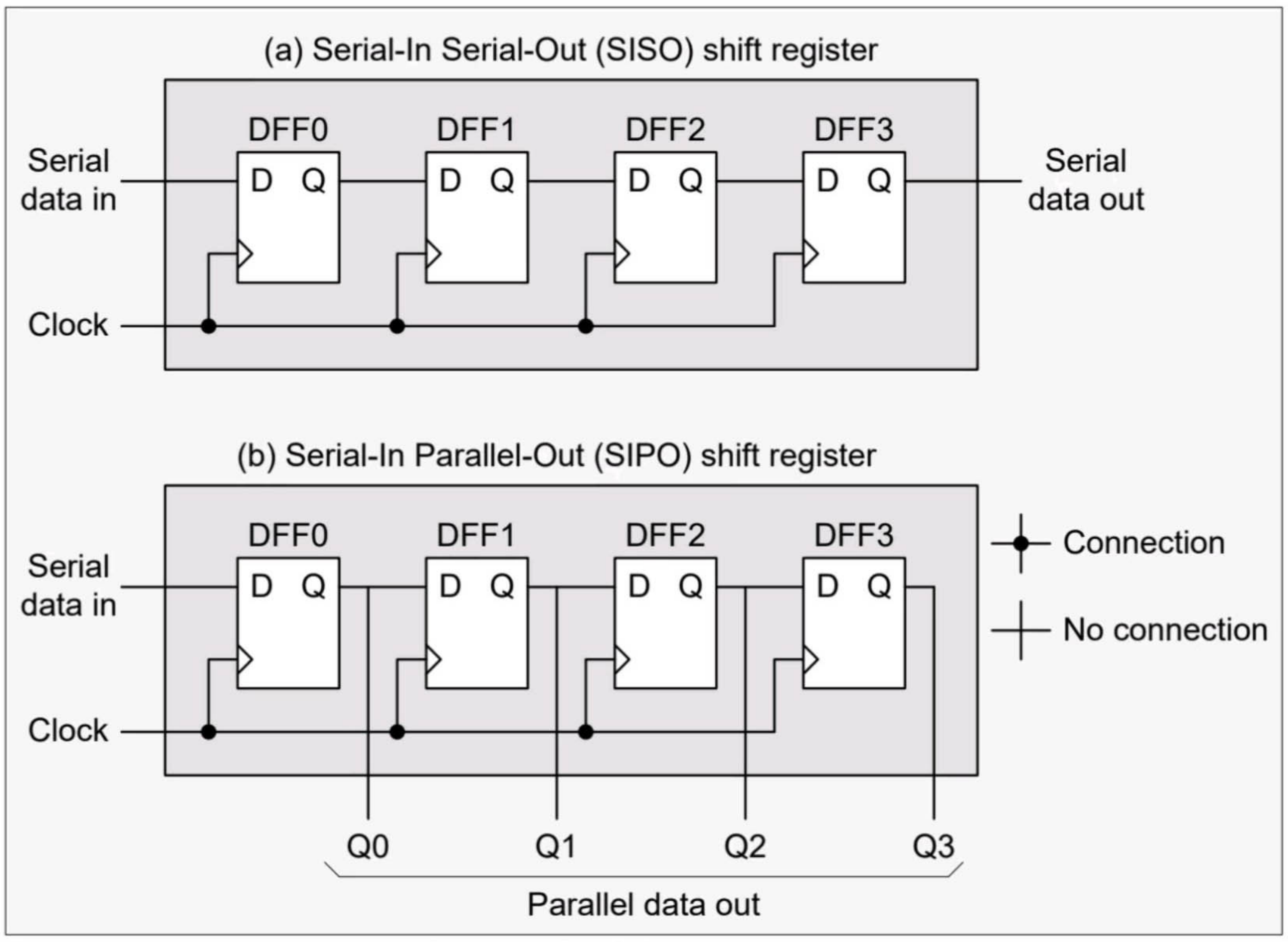


Fig.6: How to create 4-bit SISO (a) and SIPO (b) shift registers using individual flip-flips.

Shift over

We can do wonderful things using D-type flip-flops (DFFs). One of the simplest is called a shift register, in which several D-type flip-flops are daisy-chained together.

Conceptually, the simplest type of shift register is a serial-in serial out (SISO) implementation. Consider a 4-bit SISO shift register (Fig.6a). We will omit the `S` and `R` inputs to keep things simple.

An active edge on the clock line (a rising edge, in this case) causes whatever value is on the data input to be loaded into DFF0. At the same time, whatever value used to be stored in DFF0 will be loaded into DFF1, DFF1's value into DFF2 and DFF2's value into DFF3, at which point it will appear as the serial data output.

This all works due to the internal delays associated with the flip-flops. These delays mean it takes time for the new value loaded into a flip-flop to propagate to its output. So the next flip-flop in the chain has time to load the old value being presented to its input before that value changes. Pretty nifty, huh?

It takes only a slight modification to create a serial-in parallel-out (SIPO) implementation (Fig.6b). It's also possible to create parallel-in serial-out (PISO) and parallel-in parallel-out (PIPO) shift registers although a PIPO is really just a bunch of D-type flip-flops sharing a common clock.

Both examples shown in Fig.6 are unidirectional. This means they shift data in only one direction, which we could think of as 'to the right' in this case. However, it's also possible to create bidirectional versions that can shift 'left' or 'right' as defined by a control signal.

We can even create a 'universal' shift register that supports bidirectional serial-in serial-out as well as parallel-in and parallel-out if we want to get fancy.

Did someone ring?

It's taken us a long time to get here, but we can easily modify a SIPO shift register to create a function called a ring counter. For example, consider a 10-bit ring counter as illustrated in Fig.7.

The first thing to note is that the `Init` ('initialise') signal is connected to the `S` (Set) input on the first flip-flop and the `R` (Reset) inputs on the

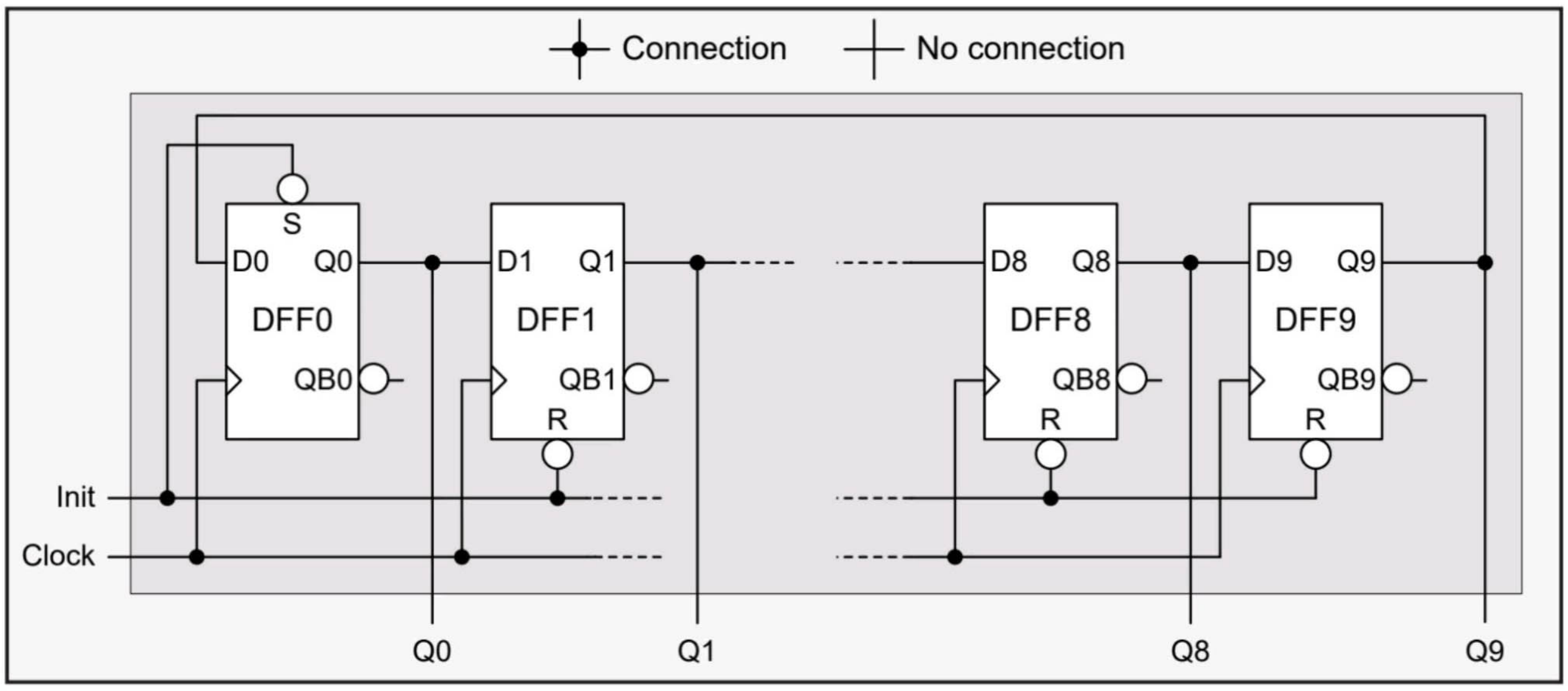


Fig.7: A 10-bit ring counter implemented using 10 D-type flip-flops.

remaining flip-flops. This means that when the `Init` signal is placed in its active-low state, our ring counter will be loaded with a value of 1000000000.

The second thing to note is that the `Q` output from the last flip-flop is fed back to the `D` (Data) input to the first flip-flop.

This means that once the counter has been initialized, clocking it will result in the 1 value circling around the counter: 0100000000, 0010000000, 0001000000 (and so on), 0000000010, 0000000001 and back to 1000000000 again.

Now think back to our clock project. If we had ten 7-segment displays, each equipped with its own transistor, we could control these ten transistors with the outputs from our ring counter, cycling through them one at a time.

In a crunchy nutshell, this technique means we can multiplex ten displays using only two of the Arduino's pins to drive the counter's `Clock` and `Init` signals.

In fact, we could control any number using just these two pins by adding or removing flip-flops to/from the chain. There is essentially no limit.

One of the downsides to this implementation is that the more displays we add and multiplex in this way, the dimmer they all get because each will receive a smaller 'slice' of the 'time pie'.

In the fullness of time (no pun intended for once), we will return to the concept of using shift registers to control our 7-segment displays. However, we will do so in a different manner to the one discussed here; the discussions above primarily serve to provide us with points to ponder for the moment.

And now, believe it or not, just when you least expected it, it's finally time to turn our attention to binary-coded decimal (BCD) – hurrah!

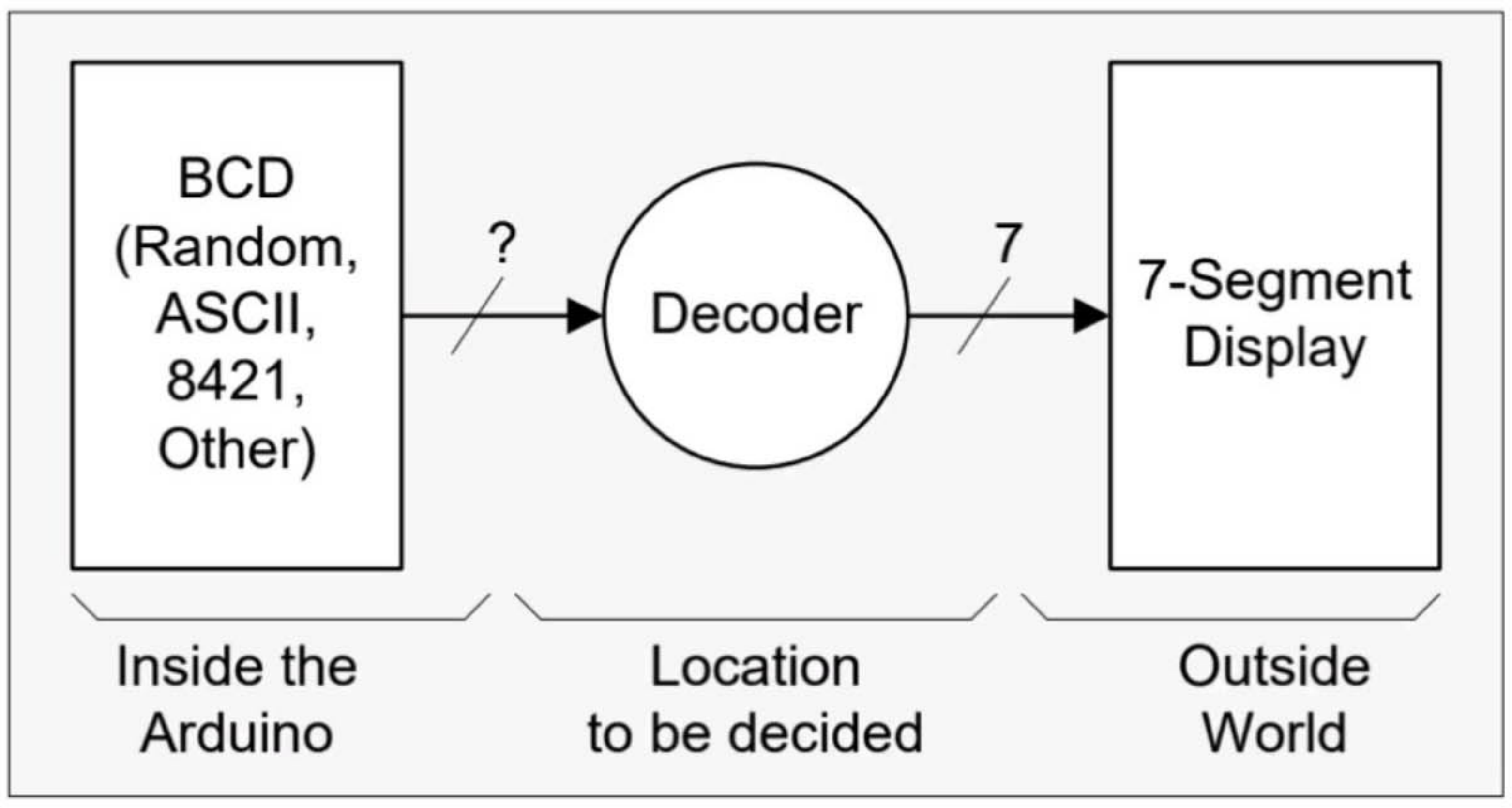


Fig.9: A high-level view of the decoding process.

Peeling an onion

The topic of BCD is a bit like peeling an onion. Why? Well, in addition to its ability to make our eyes water, there are lots and lots of layers. Many discussions on BCD skim only the outermost layer, but we are made of sterner stuff.

Let's start off by pondering what we mean by 'binary coded decimal' (BCD) in the first place.

In its most general sense, this simply refers to a class of binary encodings in which each decimal digit is represented by a fixed number of binary bits (usually 4 or 8, but other widths may be employed).

The left-hand column of Fig.8 shows the ten decimal digits we wish to encode.

Purely for the sake of an example, I generated a set of ten random binary numbers along with their hexadecimal (hex) and decimal (dec) equivalents (Fig.8a). This certainly qualifies as BCD, although it is probably not very useful.

First developed in the early 1960s, the American Standard Code for Information Interchange (ASCII) is a format used to store text in a way that most computers can interpret.

ASCII can be used to represent letters, numbers, punctuation characters, and control codes. The subset of ASCII used to represent the decimal digits also qualifies as a form of BCD (Fig.8b).

Having said all this, as we discussed in an earlier column (*PE*, April 2023), the simplest and most intuitive form of BCD is based on using the natural binary counting sequence, which is why this may be referred to as Simple BCD (SBCD) or Natural BCD (NBCD).

This is also known as a 'weighted code' because each binary digit has a weight associated with it. From most-to least-significant, these weights are 2^3, 2^2, 2^1, and 2^0. Since these weights equate to 8, 4, 2, and 1, respectively, this is also known as "8421 Encoding" or "BCD 8421".

If you wish to delve deeper into BCD, may I be so bold as to recommend reading my *Mysteries of the Ancients: Binary Coded Decimal (BCD)* column (**https://bit.ly/3XNp3uO**).

Soft or hard?

It's important to understand that BCD can be used for all sorts of things. In our case, we wish to take BCD representations stored inside our Arduino Uno and use them to drive one or more 7-segment displays.

Furthermore, the 7-segment displays we decided to use for our experiments require us to control each of their segments individually (it's also possible to purchase displays equipped with internal decoders).

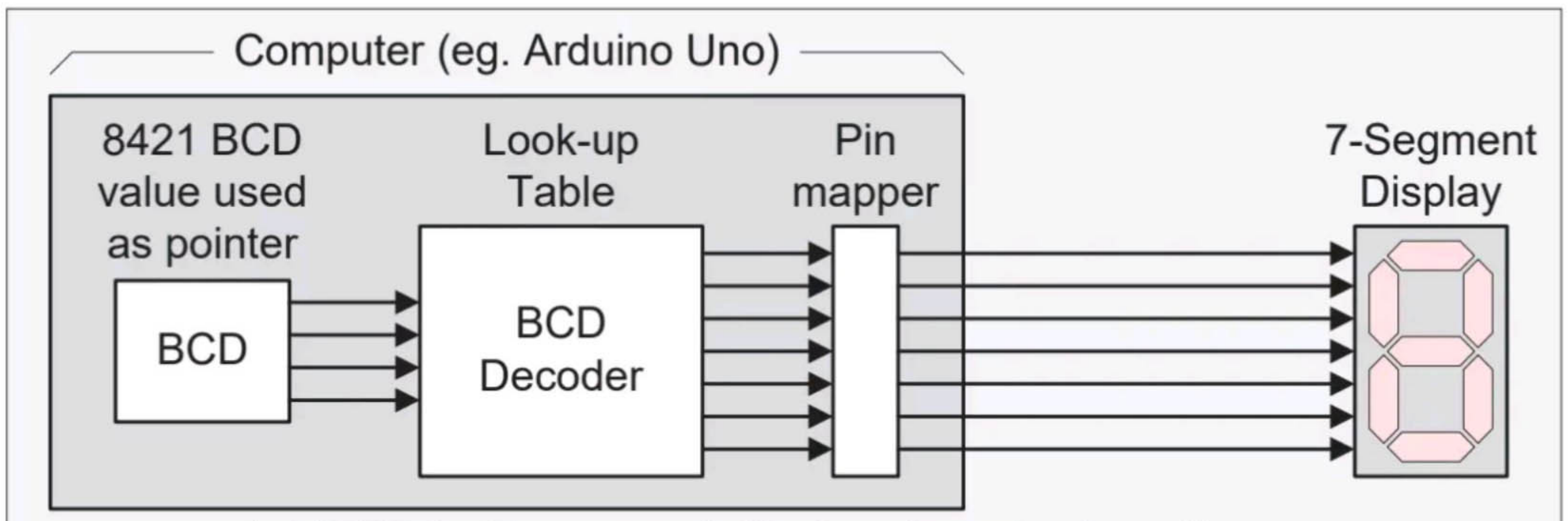
For the moment, let's consider things at a high level of abstraction. On this basis, irrespective of the BCD encoding scheme we decide to employ (random, ASCII, 8421 etc), we know we want to decode these values into the 0s and 1s that we need to control the segments on our displays that form the digits (see Fig.9).

Decimal	(a) Random			(b) ASCII			(c) NBCD / SBCD		
	Binary	Hex	Dec	Binary	Hex	Dec	8 4 2 1	Hex	Dec
0	1 0 1 0 0 1 1 1	A7	167	0 0 1 1 0 0 0 0	30	49	0 0 0 0	0	0
1	0 0 0 0 1 1 1 0	0E	14	0 0 1 1 0 0 0 1	31	49	0 0 0 1	1	1
2	1 0 0 0 0 1 1 1	87	135	0 0 1 1 0 0 1 0	32	50	0 0 1 0	2	2
3	0 0 0 1 0 0 1 1	13	19	0 0 1 1 0 0 1 1	33	51	0 0 1 1	3	3
4	0 0 0 0 1 0 0 0	08	8	0 0 1 1 0 1 0 0	34	52	0 1 0 0	4	4
5	1 1 1 1 0 0 1 1	F3	243	0 0 1 1 0 1 0 1	35	53	0 1 0 1	5	5
6	1 0 1 0 1 1 1 1	AF	175	0 0 1 1 0 1 1 0	36	54	0 1 1 0	6	6
7	1 0 0 0 0 1 1 0	86	134	0 0 1 1 0 1 1 1	37	55	0 1 1 1	7	7
8	1 1 0 0 0 1 1 0	C6	198	0 0 1 1 1 0 0 0	38	56	1 0 0 0	8	8
9	0 1 0 1 0 0 0 1	51	81	0 0 1 1 1 0 0 1	39	57	1 0 0 1	9	9

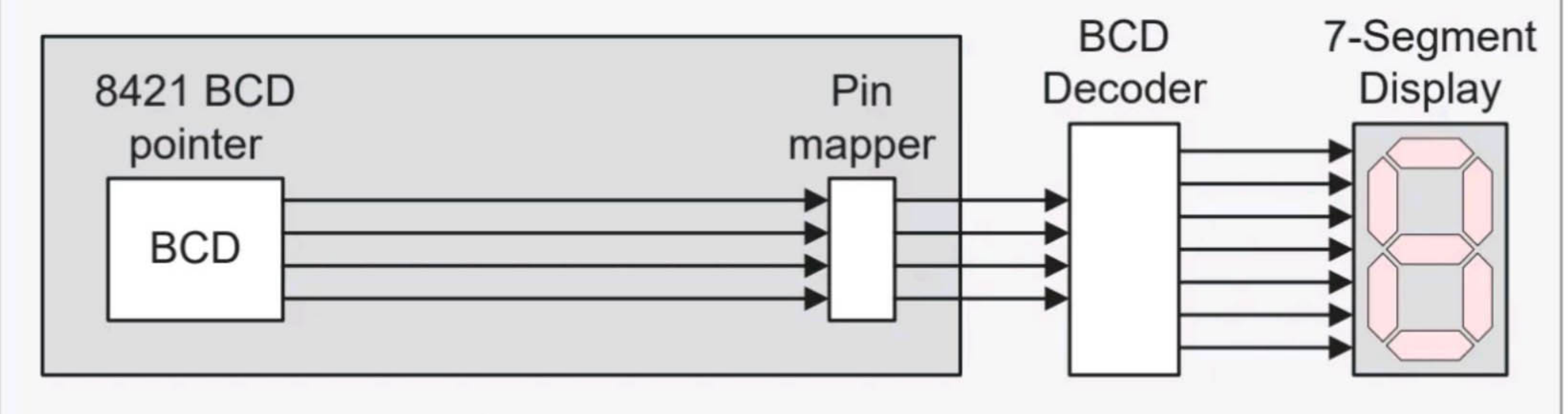
Fig.8: Three possible BCD representations (out of many). ASCII and NBCD/SBCD are the most common.

The reason we are showing a question mark for the number of wires feeding the decoder in that figure is that, as per Fig.8, that value depends on the BCD encoding scheme we ultimately decide to use.

Note that the reason we are showing only seven wires feeding the 7-segment display is that a traditional

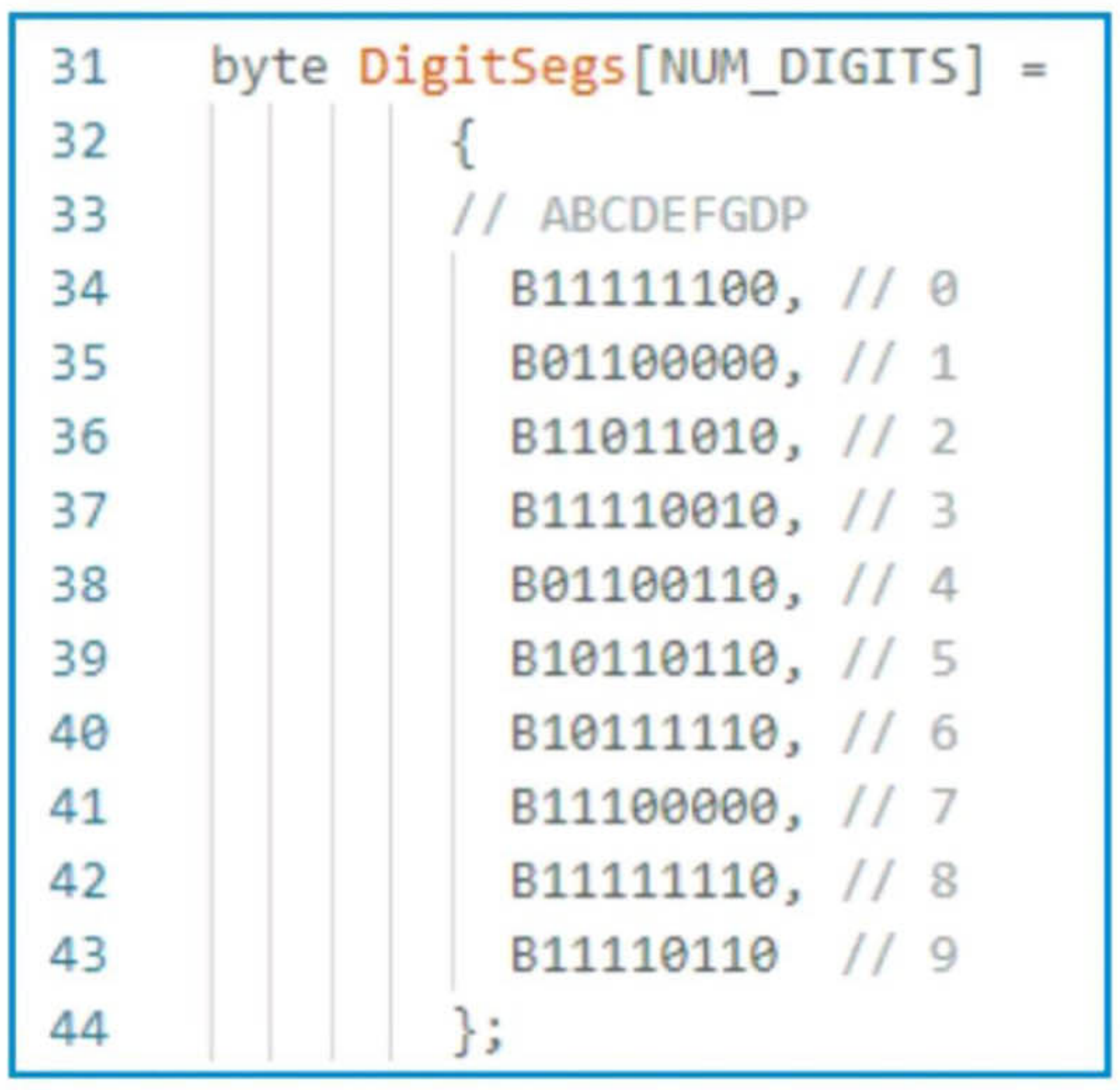


(a) BCD to 7-segment display decoder in software



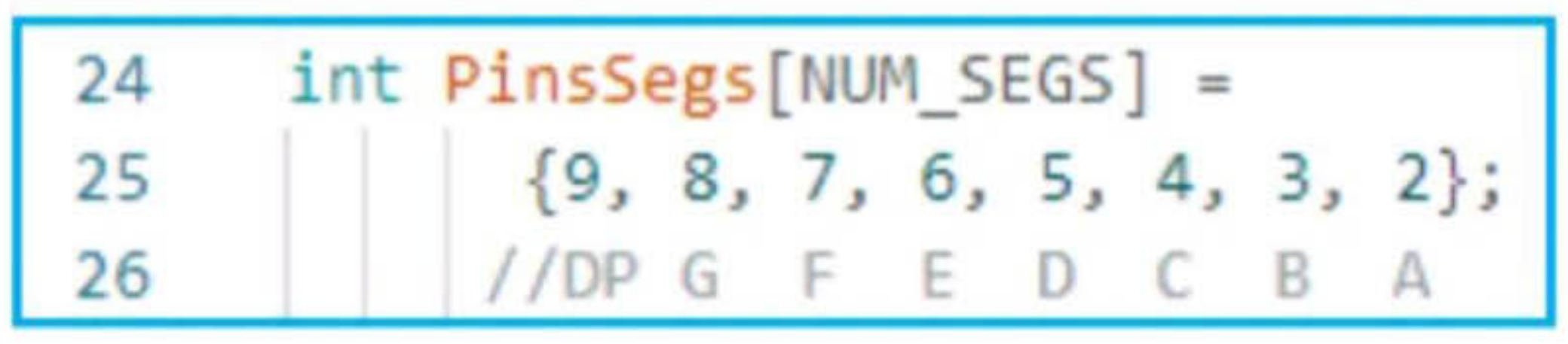
(b) BCD to 7-segment display decoder in hardware

Fig.10: Software vs hardware 7-segment decoder implementations.



```
byte DigitSegs[NUM_DIGITS] =
  {
  // ABCDEFGDP
    B11111100, // 0
    B01100000, // 1
    B11011010, // 2
    B11110010, // 3
    B01100110, // 4
    B10110110, // 5
    B10111110, // 6
    B11100000, // 7
    B11111110, // 8
    B11110110  // 9
  };
```

Listing 1: Our software look-up table (LUT).



```
int PinsSegs[NUM_SEGS] =
    {9, 8, 7, 6, 5, 4, 3, 2};
    //DP G  F  E  D  C  B  A
```

Listing 2: Our software pin mapper.

BCD decoder has no knowledge of the display's decimal point segment.

How are we going to create the decoder portion of this puzzle? There are two main options: a software realisation internal to the Arduino (Fig.10a), or a hardware implementation external to the Arduino (Fig.10b).

Thus far in our experiments, we've been employing a software decoder. Specifically, we've been using classic 8421 BCD values as pointers into a look-up table (LUT) containing the 1s and 0s corresponding to the display segments we wish to activate or deactivate, respectively.

The look-up table shown in Fig.10a is the `DigitSegs[]` array we've been using in our programs that indicates which segments to light for each digit to display (see Listing 1).

The Pin Mapper functional block shown in Fig.10a is where we specify which of the Arduino's pins we are using to drive our display(s). This is the `PinsSegs[]` array we've been using in our programs (Listing 2).

It's also worth noting that our software solutions made provision to drive the display's decimal point (DP) segment, although we never got around to actually using that feature.

In the case of the hardware implementation depicted in Fig.10b, the 4-bit 8421 BCD values inside the Arduino are directly mapped onto four of the Arduino's pins.

These pins drive a hardware implementation of a BCD to 7-segment decoder, the outputs of which are used to drive the 7-segment display(s), as illustrated in Fig.11.

Components from Part 1	
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-to-male)	https://amzn.to/3O4hnxk
Components from Part 2	
7-segment display(s)	https://amzn.to/3Afm8yu
Components from Part 5	
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Components from Part 6	
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX
Components for Part 9	
SW-18010P vibration switch	https://bit.ly/46SfDA4
Components for Part 10	
Breadboard mounting trimpots	https://bit.ly/3QAuz04
Components for Part 12	
Light-Dependent Resistor	https://bit.ly/3S2430m
Components for Part 13	
BC337 NPN Transistor	https://bit.ly/40xAgyS
Components for Part 14	
HC-SR04 Ultrasonic Sensor	https://bit.ly/49AMBq4
Components for Part 15	
Real-Time Clock (RTC)	https://bit.ly/3S9OjHl
Components for Part 18	
Long tailed (0.1-inch/2.54mm pitch) header pins	https://bit.ly/3U1Vp2z
Components for Part 19	
Prototyping boards	https://bit.ly/3UMkcZ1
Kit of popular SN74LS00 chips	https://bit.ly/3wqgzyv
Components for Part 20	
16V 100µF electrolytic capacitors	https://bit.ly/44LzpNa
Ceramic capacitors (assorted values)	https://bit.ly/4bEAUiv

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Remember that our first pass at a clock design using four 7-segment displays consumed all 12 of our digital I/Os (Fig.4a).

Our next pass involved us creating and deploying a 2:4 decoder (*PE*, July and August 2024). This solution consumed 10 pins, thereby leaving two free.

Ignoring the decimal points, using a hardware BCD decoder will free up four more pins, which means we will be able to drive all four of our displays using only six pins, leaving us with six free.

Can we reduce our pin count even further? You betcha, but that will be a topic for a future column.

Next time

If we were feeling adventurous, we could implement our hardware BCD to 7-segment decoder using primitive logic gates in a similar fashion to the way in which we created our 2:4 decoder. However, I've decided that my life is adventurous enough already.

So, in our next column, we will use a dedicated BCD to 7-segment decoder IC to drive our displays.

As part of this, we will discover and discuss all sorts of interesting things.

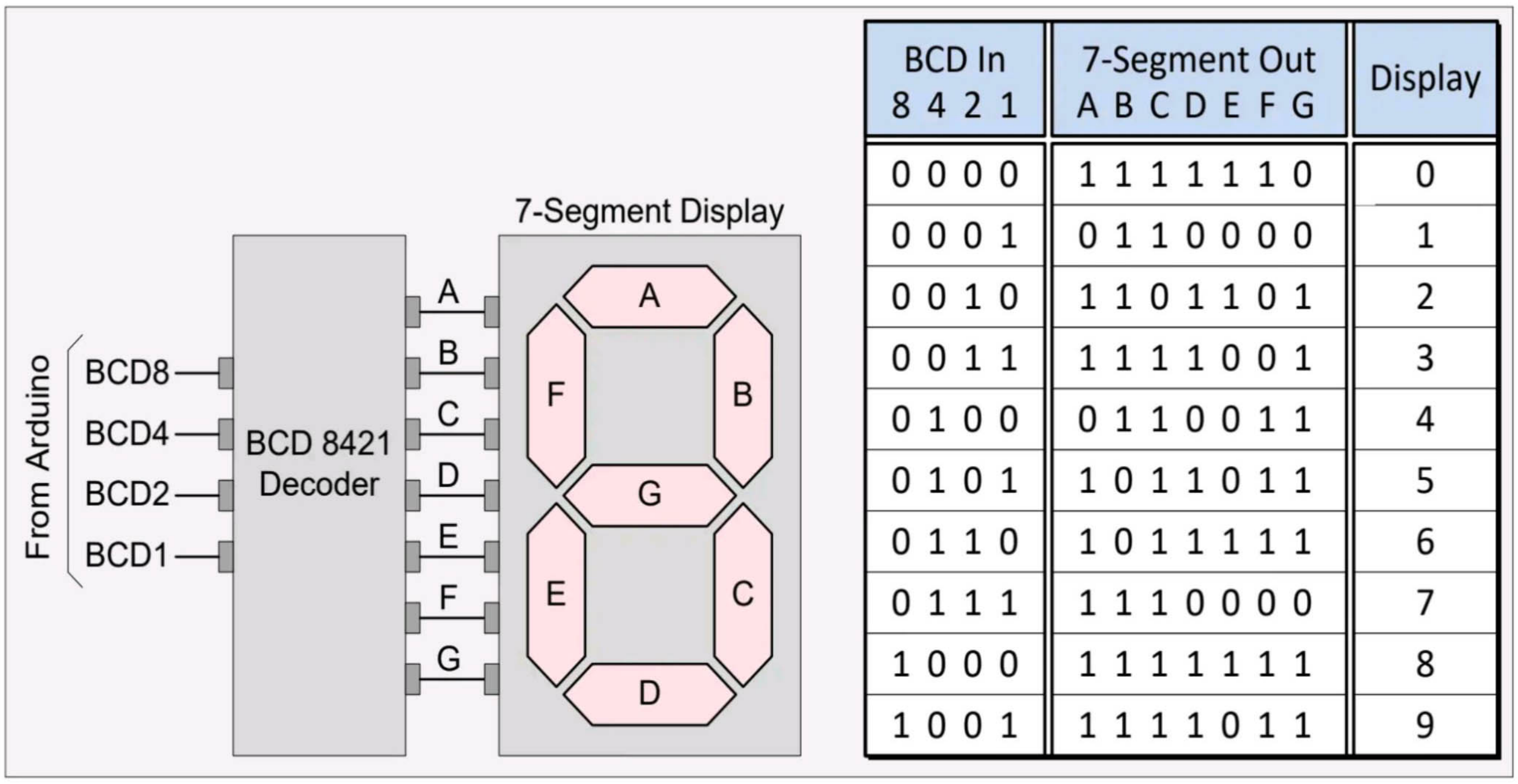
Until then, as always, I welcome any comments, questions or suggestions from our readers. **PE**

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.



BCD In 8 4 2 1	7-Segment Out A B C D E F G	Display
0 0 0 0	1 1 1 1 1 1 0	0
0 0 0 1	0 1 1 0 0 0 0	1
0 0 1 0	1 1 0 1 1 0 1	2
0 0 1 1	1 1 1 1 0 0 1	3
0 1 0 0	0 1 1 0 0 1 1	4
0 1 0 1	1 0 1 1 0 1 1	5
0 1 1 0	1 0 1 1 1 1 1	6
0 1 1 1	1 1 1 0 0 0 0	7
1 0 0 0	1 1 1 1 1 1 1	8
1 0 0 1	1 1 1 1 0 1 1	9

Fig.11: A hardware-based BCD 8421 to 7-segment decoder with its truth table.

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IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700
Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
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HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

Marconi 2955B Radio
Communications Test Set – £800

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

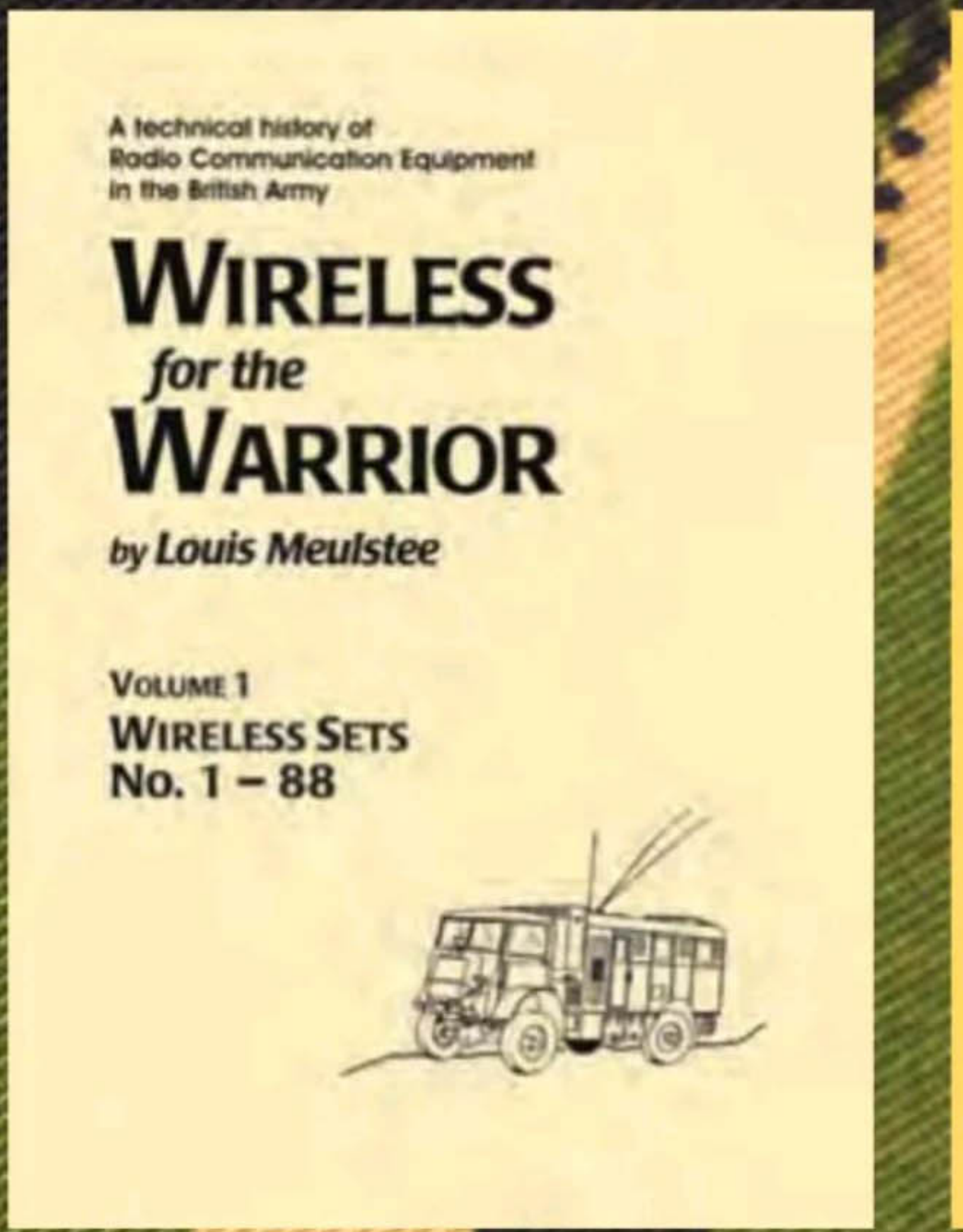
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or ‘spy’ radio equipment, sets which were used by special forces, partisans, resistance, ‘stay behind’ organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.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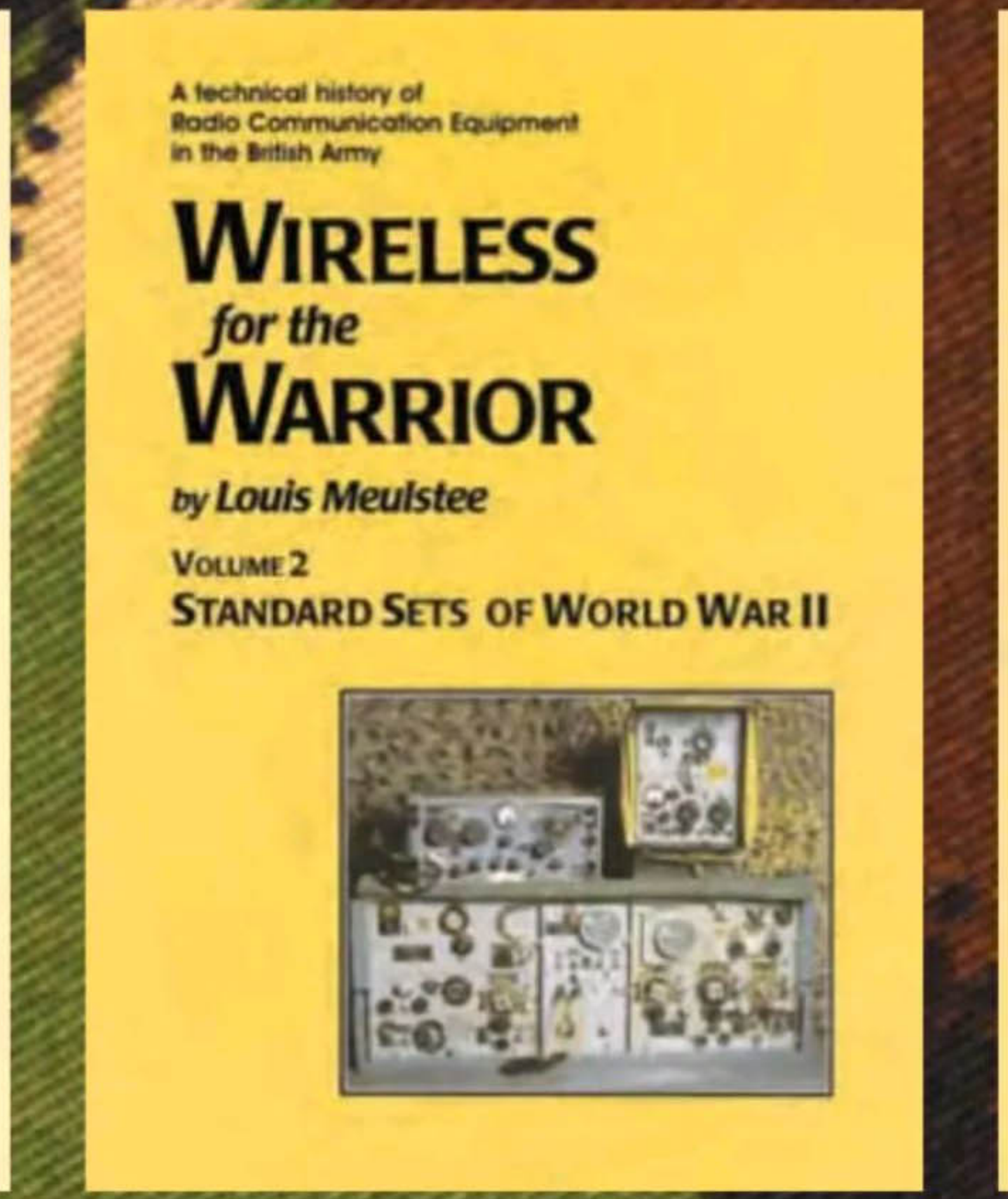
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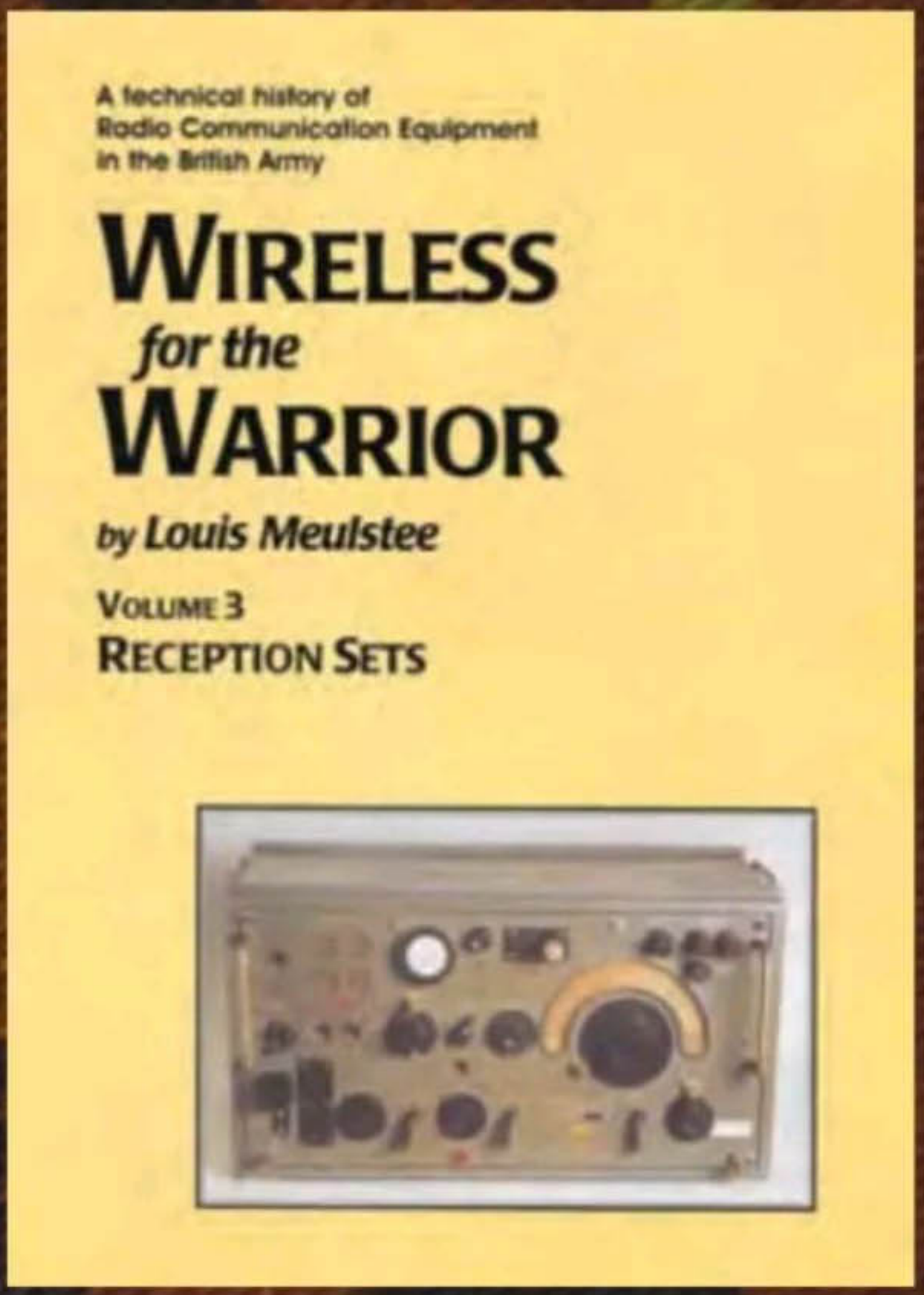
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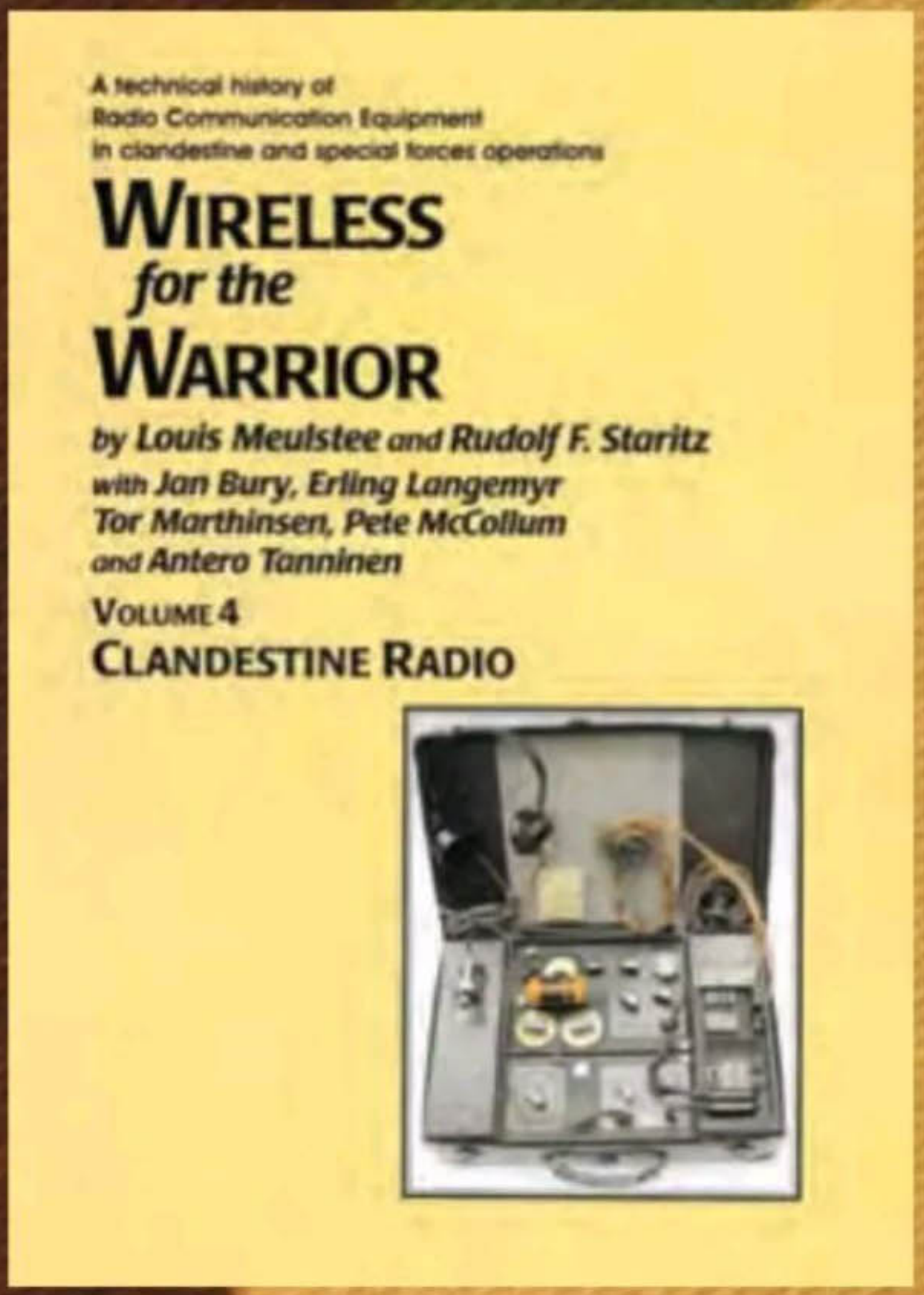
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easy to build Salad Bowl SPEAKERS

These speakers are retro, stylish and surprisingly good performers. They're also pretty easy to make and don't cost the Earth. My wife liked them so much that she actually wanted me to put them in the living room!

By Phil Prosser

Here is our take on the IKEA salad bowl speaker concept that has been spreading around the internet, which we think came out really well. This article describes a fully functioning pair of desktop/bookshelf speakers and gives some suggestions for tweaking the design to suit your needs.

What initially attracted us to this idea was the mix of an old-school spherical speaker with extreme ease of construction. While the initial motive for building these was style and looks, it quickly became apparent that these little cuties had more to offer than that.

Those who make speakers will be quick to comment that a sphere should be highly resonant; however, our tests show this is not the case. The fact that the driver forms a significant portion of the surface area of the sphere results in the Q of the internal resonance being relatively low. As a result, our measurements don't show resonant peaks in the response.

Another benefit of a spherical speaker is that it has no edges. Or is it all one edge? Either way, concerns like edge diffraction and baffle effect are avoided. The fact that these speakers are spherical makes them extremely rigid.

Edge diffraction is the effect of sound waves propagating from the driver across a speaker's front panel, then hitting the edge, which forms a discontinuity from propagation in 'half space' to 'free space'. This change causes diffraction at the speaker edges, affecting the frequency response and off-axis behaviour.

There are many ways a spherical speaker can be mounted. Without creating a solution to this, they will tend to roll around! We have come up with a couple of options, including feet for the desk version and "rocket" floor stands, both shown in the photos. The desktop version uses three small doorknobs as feet.

The loudspeaker driver used is the SB Acoustics SB12PFCR25-4-COAX, a bass/mid driver with a coaxial tweeter (mounted in the centre). This allows us to achieve really good performance from about 70Hz upwards. These work brilliantly as desktop speakers and would also match well with any of our subwoofers crossed over at 80-100Hz.

If you're interested in matching these speakers with a subwoofer, Silicon Chip magazine published my Tapped Horn Sub design in its September 2021 issue; it is inexpensive and easy to build. You could also consider the very high-performance Active Subwoofer that was published in PE in January & February 2024.

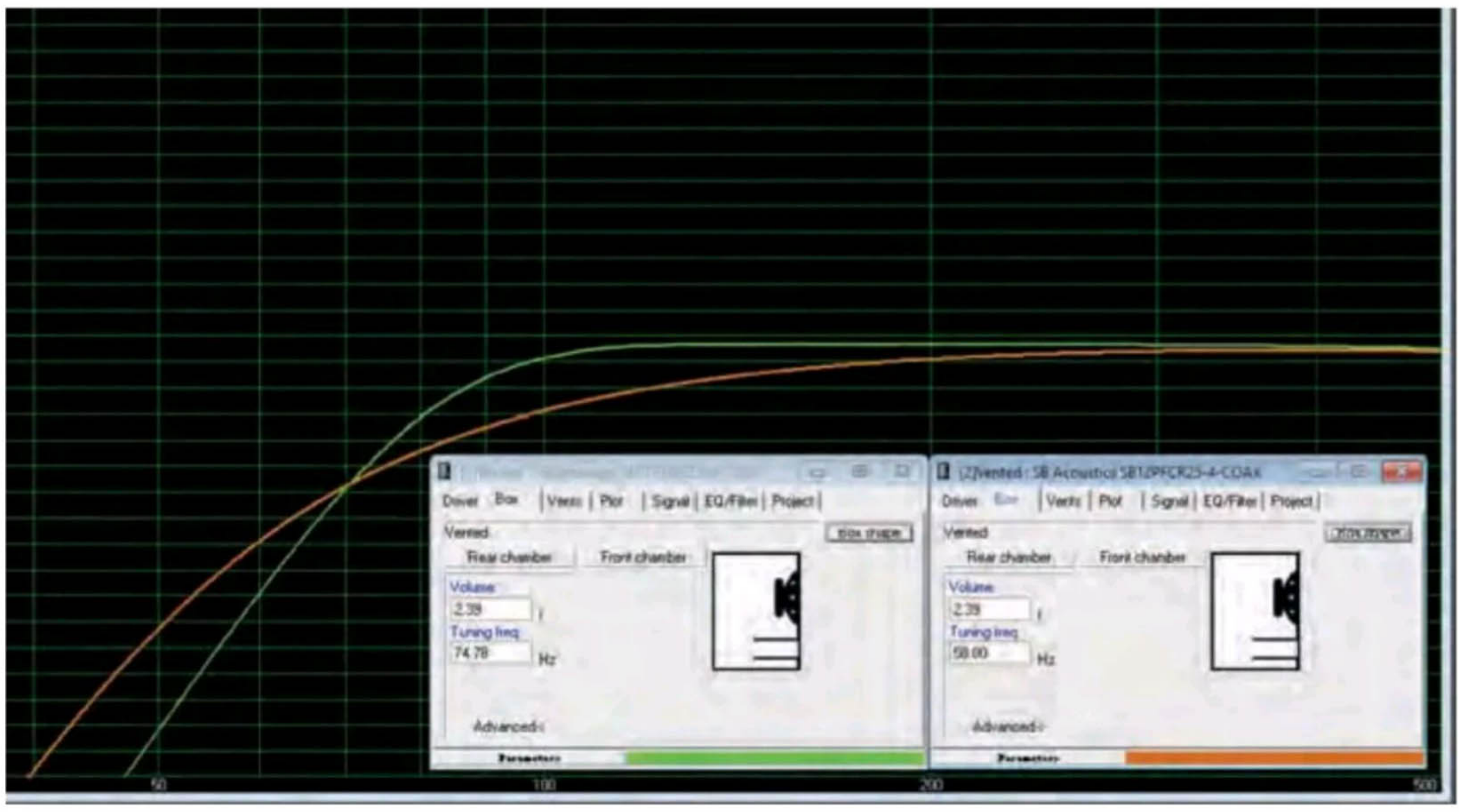
We chose this specific SB Acoustics driver because it incorporates the tweeter, and neatly addresses the challenge of finding somewhere to mount the tweeter. The only other solution we could think of was to mount the tweeter externally, which we did with the floor-standing version, but it was a real hassle.

We have added a port to our enclosure. This allows us to extend the lower frequency response to about 70Hz, with some useful output below that. That is a good result for such a small speaker and is reasonable in its intended applications of desktop usage or placement in a small room. Don't try to run a dance party using these speakers, though.

There is a bit of a hump in the frequency response in the 100-200Hz region. This is a result of the port and helps fill out the bottom end, given the roll-off below 80Hz. The

Features & specifications

- *Compact full-range loudspeakers with a unique appearance*
- *Simple construction*
- *Spherical enclosure minimises diffraction*
- *Coaxial tweeter for good off-axis response*
- *Can be desk or floor mounted (the latter with a simple stand)*
- *Frequency response: 70Hz to 20kHz (±3dB typical)*
- *Power handling: 50W RMS per channel*
- *Impedance: nominally 4Ω*
- *Relatively low total cost*



Vented
Volume: 2.39 l
Tuning freq: 74.78 Hz

Vented
Volume: 2.39 l
Tuning freq: 58.00 Hz

Fig.1: the modelled response of these Speakers with a 90mm port (green curve) or tuned for 58Hz with a 160mm port (orange curve). The longer port gives more output below 70Hz, but trades that off against reduced output between about 70Hz and 200Hz.

black line in Fig.2 shows the low-frequency response you will achieve if you simply omit the port. If you use these on a desk backed up to a wall, omit the port.

We used a 25mm bass reflex port cut to 90mm in length. This tunes the system to resonance at 74Hz. In practice, the vent ends close to the driver magnet, so its effective length is over 90mm. This tuning gains us a couple of decibels of extra bass in the roll-off region.

In an ideal world, this port would be 160mm long, tuning the enclosure to 58Hz, but there is not enough room in the enclosure for that - see Fig.1.

Cost

While these speakers are designed to be relatively inexpensive, we are using high-quality drivers from SB Acoustics that cost around £45 each. We also can't avoid some relatively expensive air-cored inductors in the crossover, meaning the total cost to build these speakers will be about £350. Still, it's hard to buy a decent pair of speakers for less than that.

You might be able to build a pair for around £180 or perhaps a bit less if you take some shortcuts, eg, if you come up with alternative feet and wind your own air-cored inductors.

Crossover

The crossover we're using is based on that recommended by SB Acoustics with some minor modifications. This is a third-order electrical crossover at 2.2kHz. Third-order is a higher order than we would generally want to use. Still, given that the tweeter resonance is at 1300Hz, it's necessary for the crossover to occur at a sensible frequency.

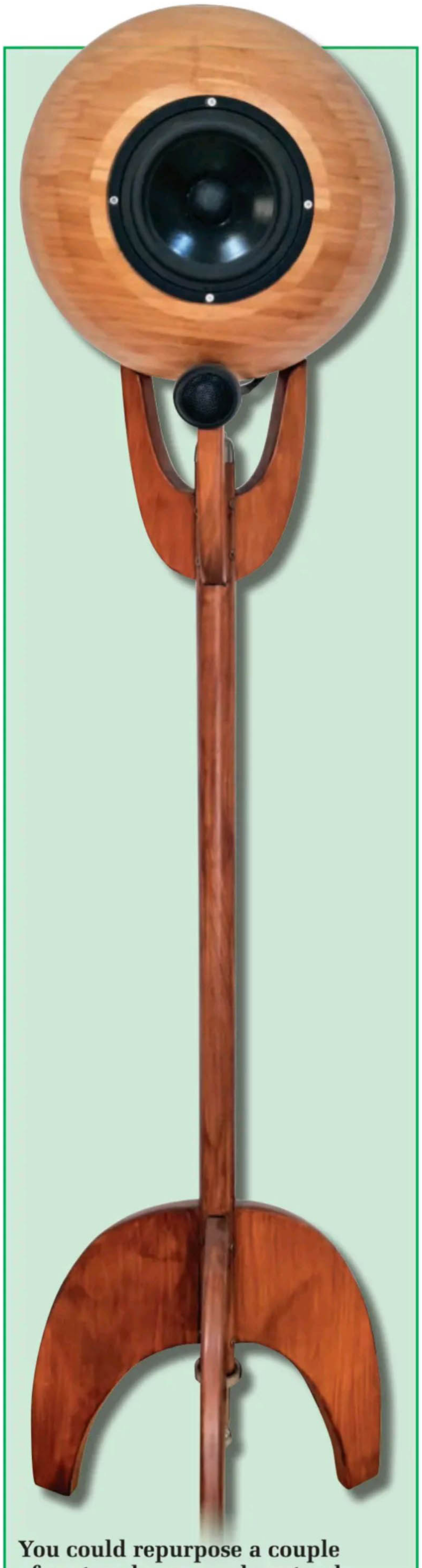
Our measured frequency response of the driver in the spherical enclosure (Fig.2) is very close to that SB Acoustics provides. The only notable difference is that our tweeter was 1-2dB less sensitive than theirs.

Fig.2 is a raw measurement of the driver with no processing at all. We are looking for spikes and dips that, if present, will colour the sound. Happily, the response is actually very smooth. We will discuss that chasm at 12kHz or so later; the short answer is that it disappears off-axis. Those wobbles in response at the bottom end are due to floor and room interactions.

We were about to start a fresh crossover design when we noticed that SB Acoustics published a recommended crossover circuit. When a manufacturer publishes a reference design, it is usually a great starting point. We duly tested it.

Given the tweeter's small diameter, a third-order design was appropriate. It is important to drive as little energy at 1.2kHz into that tweeter as possible. The woofer also has a third-order crossover, which makes sense from a symmetry perspective. This driver is well-behaved, as shown in Fig.2. So, if not for the tiny tweeter, a second-order crossover may have been better.

The resulting system response is shown in Fig.3. This is very flat



You could repurpose a couple of coat racks as speaker stands since the Speakers are small and light, or build similar stands from MDF or other timber. We used a driver without a coaxial tweeter and mounted the tweeter under the enclosure, but it doesn't look great and is fiddly to assemble. We therefore recommend you stick with the coaxial drivers.

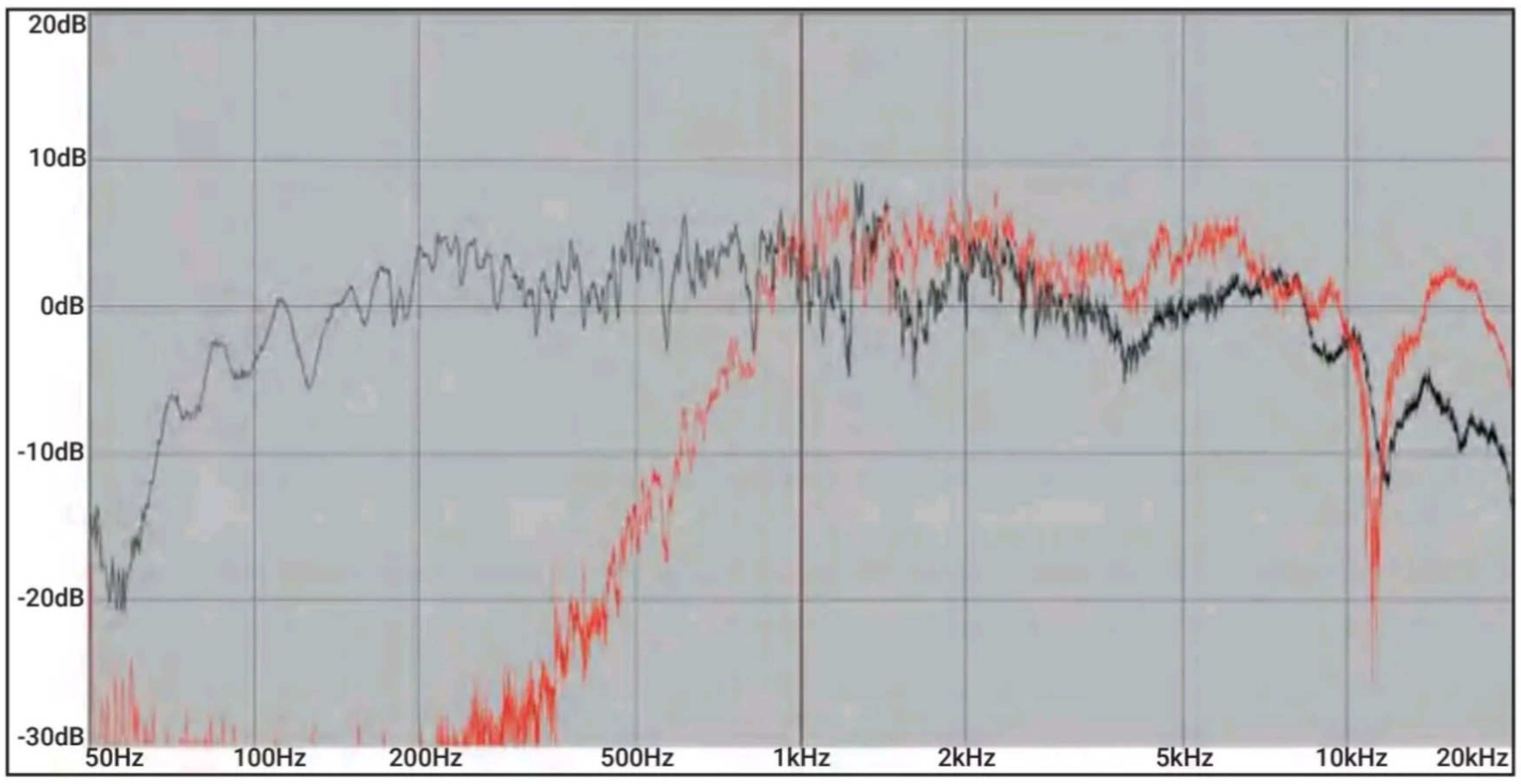


Fig.2: the measured frequency response of the SB Acoustic SB12PFCR25-4 driver without any processing or smoothing. The woofer response is in black, while the tweeter is in red. The dip above 10kHz is discussed in the text.

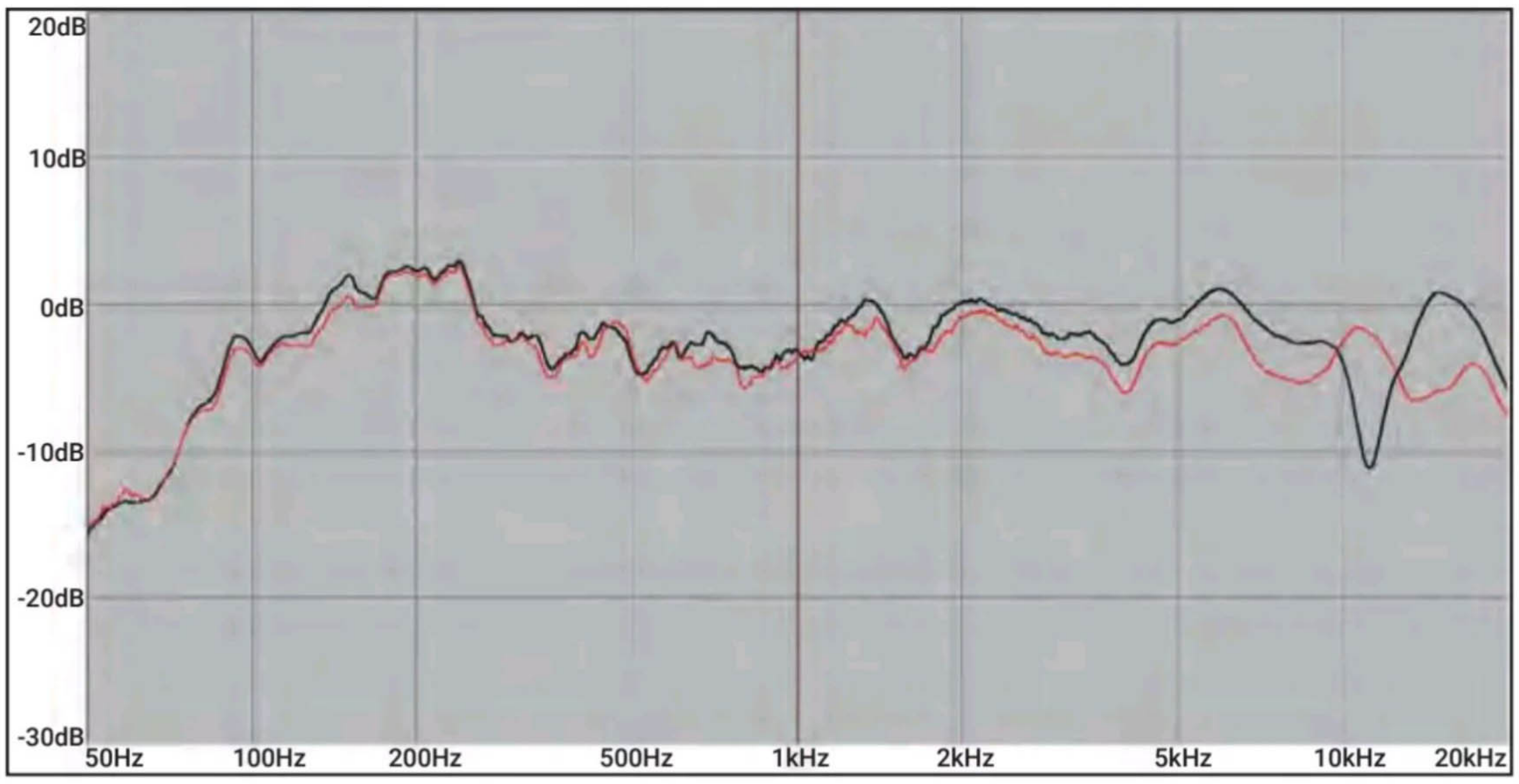


Fig.3: the overall Speaker frequency response with ⅙th octave smoothing, with on-axis response in black and 15° off-axis in red. This is very good for such a simple design. The dip at about 12kHz is a consequence of the tweeter location. As the crossover is optimised for a 15° off-axis response, that dip has disappeared in the red curve.

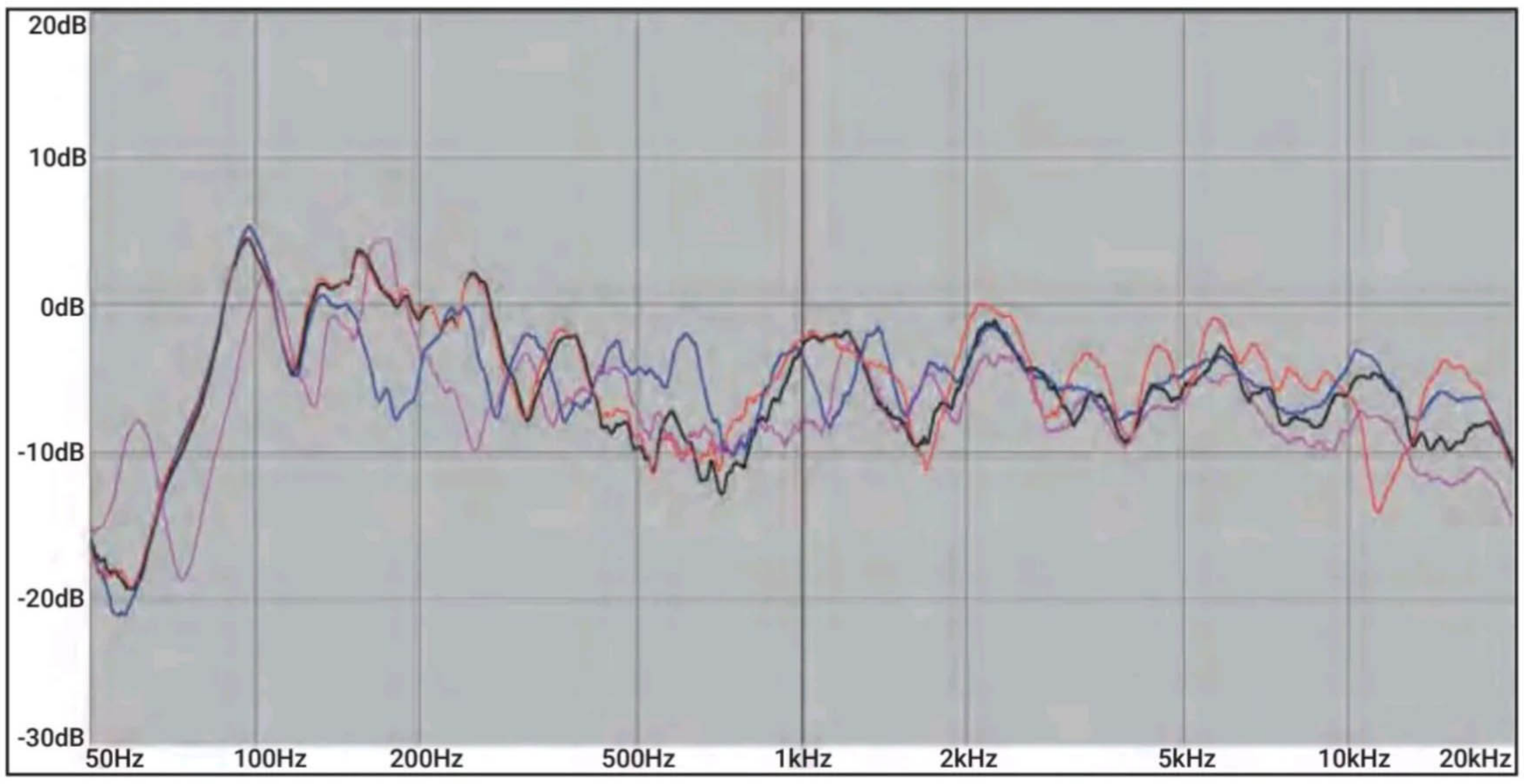


Fig.4: the frequency response of a Salad Bowl Speaker with ⅙th octave smoothing and reflex port installed at various locations. The black curve is about 15° off-axis, red is straight on, blue is elevated about 400mm and again about 15° off-axis, and purple is on the other side of the desk at a similarly elevated location. The low-frequency ripple from the room is very evident.

through the main audio range, up to 10-15kHz. The dip between 10kHz and 20kHz can be seen to move as you move off-axis. This is likely a consequence of the coaxial tweeter and varying path lengths from the exit of the coaxial tweeter to the woofer voice coil former.

It is important to note that there is no sign of the crossover at 2.2kHz in the frequency response plot. In short, this crossover works very well with the driver.

The following hypothesis hasn't been proven, but the wavelength of 12kHz is about 27mm, and destructive interference will occur for a path difference of 10-15mm. Given the location of the tweeter cone relative to the coil edge, the dip makes sense. It also explains why the dip changes in frequency and disappears as you move off-axis.

This ripple in response is at a frequency near the limit of what most people can hear, so it is not a big deal.

Our frequency response plot was made 1.2m above the floor at a distance of 30cm, the same distance at which the manufacturer's response plots were made. When used on a desk, as we expect these will be, there is no sign of that dip. It's only apparent when the driver is measured in free space.

There are all sorts of other artefacts in the plots, which, in our test location, resulted from our monitor, keyboard and probably even coffee cup! These peaks and dips move all over the place as you move around the Speaker. Running the risk of being told to clear our desk, Fig.4 shows several measurements of the Speaker in different locations.

Subjective evaluation

These speakers sound pretty darn good using the standard crossover. We did make two minor changes, though. Firstly, we reduced the tweeter attenuation resistor to boost treble by 1dB. Also, the OEM design used a 0.4mH series inductor for the woofer. We had a bunch of 250μH units available, and calculations showed it would make a negligible difference, so we went with that.

Given how well these measured, we shelved any idea of redesigning the crossover. Why break something that works? The final crossover is shown in Fig.5.

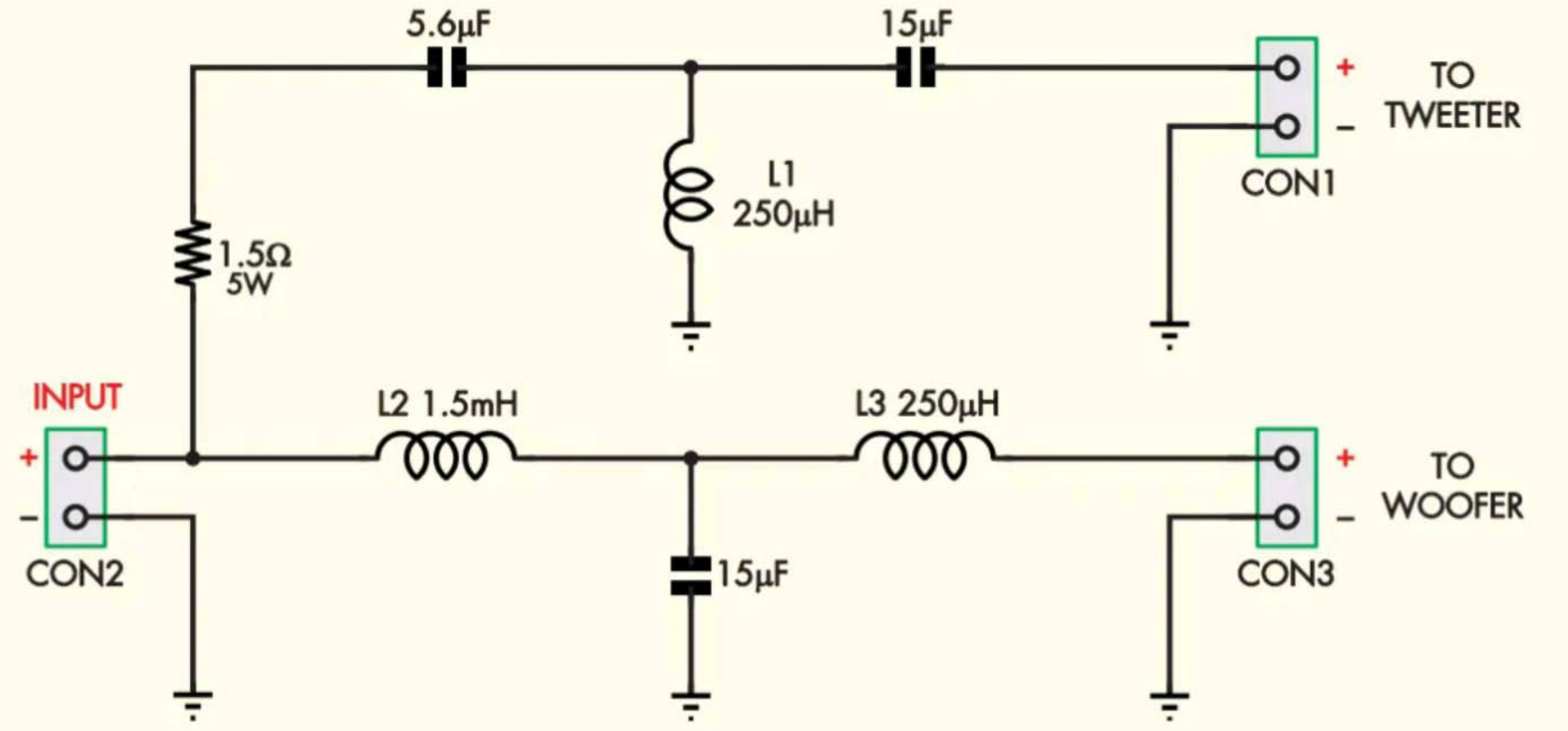


Fig.5: the crossover circuit provides a third-order high-pass filter (HPF) for the tweeter and a third-order low-pass filter (LPF) for the woofer, crossing over at about 2.2kHz. There is no phase inversion. We have made the resistor 1.5Ω as that provided better balance in our speakers than the suggested 2.2Ω. Still, if your tweeters are less or more sensitive than ours, you may wish to tweak its value.

The change from 2.2Ω to 1.5Ω for the tweeter series resistor will increase the tweeter output by about 1dB and slightly improves damping. Given the frequencies involved, it is not likely that the reduced sensitivity is a consequence of the spherical enclosure; it could be that our samples are slightly less efficient than average (or the ones they tested were above average in efficiency).

When building yours, consider experimenting with values of, say, 1Ω, 1.5Ω and 2.2Ω to see which results in the most natural sound in your application.

Practical considerations

The mounting location for the crossover was a bit of a head-scratcher. Usually, we would make a PCB and screw it to the enclosure. That is not an option here as, being spherical, there are no flat surfaces to use. There is also precious little room to play with.

So we made a PCB with rounded edges that you can glue into the speaker base. It just fits through the driver hole, and we have placed the 1.5mH inductor so that you can snug this up against the port and glue them together – see Photo 1. We used neutral-cure silicone sealant to glue the crossover PCB to the enclosure, as it will stick to just about anything, and once it sets, it is very resilient.

Building the speakers

The sole ‘tricky’ part of building these speakers is cutting the bottom off one bowl to accommodate the driver. If you have a router or can borrow one, it will be much easier than you might think. We reckon it would be possible to use a tenon saw and do this by hand if you clamp the bowl well, as the bowl wall is only 8mm thick.

When we cut off the bottom of the bowl to accommodate the speaker driver, we need sufficient material left to screw into. To achieve this, we took an MDF off-cut and cut it into two 120mm circles using a jigsaw. We then used an 80-grit sanding disc in a drill to get them to be rough fits to the bowls – see Photo 2. The fit does not need to be perfect; we will glue it in with acrylic filler.

Use an N95 mask and work outside (if possible) when cutting and sanding MDF. Having a vacuum cleaner pick up the sawdust as you make it is also a good idea. MDF dust is a health hazard.

Once you have roughed the wood so it fits with a gap under, say, 5mm, apply acrylic filler liberally around the sloped section and squeeze it into the bottom of the bowl, as shown in Photo 3. It is a good idea to drill a hole in the middle of the MDF to allow air out as you stick it in. Leave it for a week to really set.

Routing

We used a circle jig (described on page 37 of the January 2024 issue) and a router to expand the flat portion of the bowl base to an outer diameter of 122mm, matching the diameter of the SB12PFCR25-4-COAX driver. We placed the bowl top-down on the workbench and drilled a hole in the middle of the base to centre

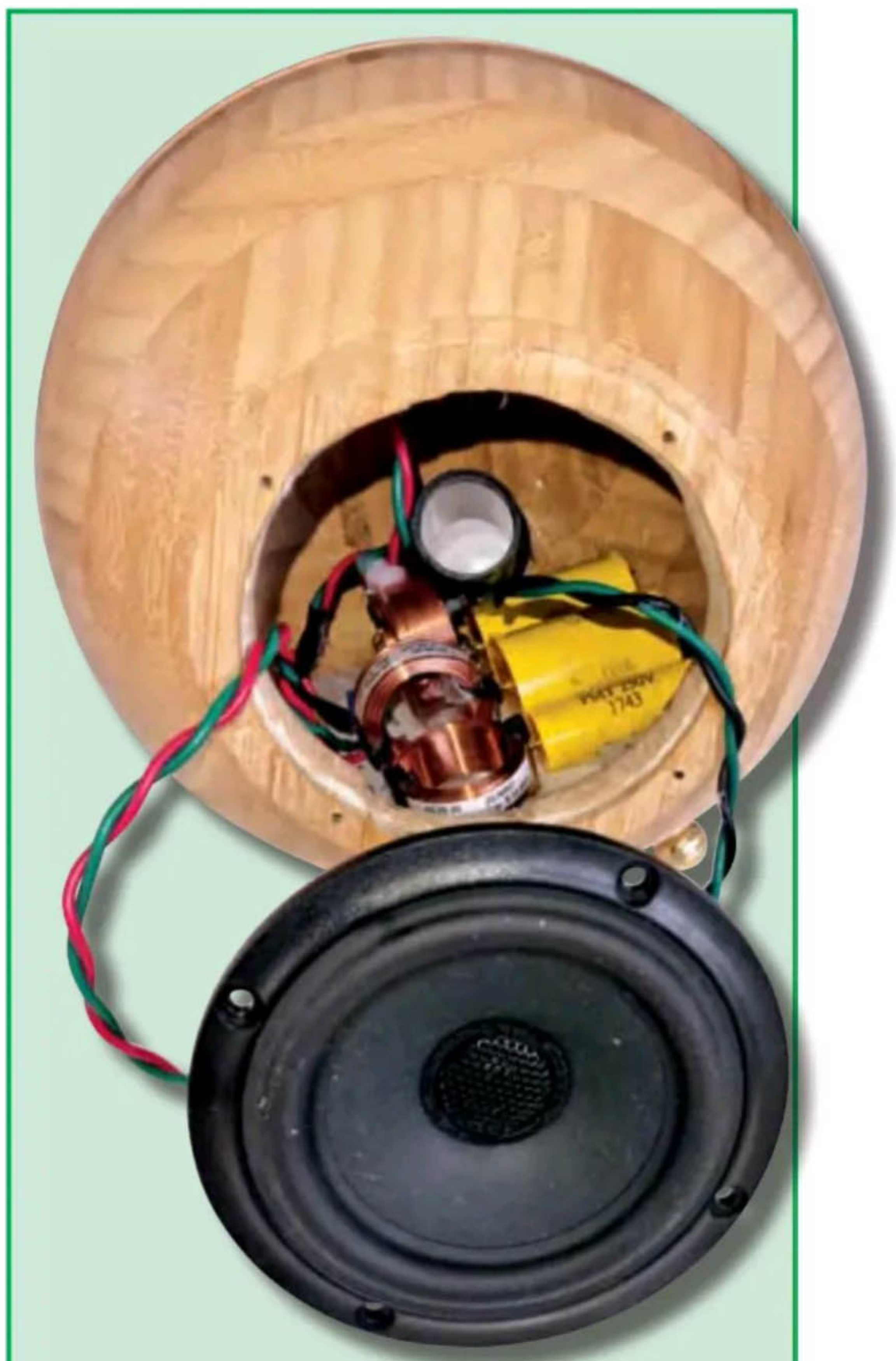


Photo 1: you can see how the port, driver and crossover fit into the spherical enclosure that was made by gluing two salad bowls together. You can also just see the MDF reinforcement ring behind the circular driver cutout.

Photo 2: we roughly cut two 120mm MDF discs from off-cuts (left), then used an 80-grit sanding disc in a cordless drill chuck to shape it to fit in the bottom of the bowl (right).

Photo 3: the reinforcement disc is glued into the bottom of the bowl using acrylic gap filler. Before doing this, ensure it is a close fit, leaving gaps less than 5mm wide all around.

the router. Make this route in two or three cuts, and do not cut too deep.

Briefly, the circle jig is a length of aluminium bar with holes drilled in it to allow it to be bolted to the router. There are other holes drilled in it at various distances from the router. After loosely screwing one of these into a centre hole drilled in the bowl, the router will rotate about that point and make a perfect circle.

We are pretty sure that a steady hand, some clamps and a tenon saw would do the job, and might actually be easier and make less mess.

Cutting the speaker hole

The driver fits into a 102mm hole in the base, visible in Photo 4. Mark this with a compass and cut it with either a handsaw or jigsaw. The hole is fairly small, so only a little elbow grease would be expended doing this by hand. Check that your driver fits, and if necessary, fettle (a fancy word for bodge) the cutout so that the terminals do not interfere with the hole.

Fitting the port

If we were using these on a desk, pushed back against a wall, we would omit the port. The boost in low frequencies using the Speaker in a corner will be sufficient, and you will be better off without the port. If you've already added the port, you could put a sock in it for such use cases.

If you will use the speakers in more 'free space' and without a subwoofer, include the port, as the low-frequency output will benefit from it.

If adding a port, drill the hole now. We used a 32mm hole saw and filed the hole to the required 33mm. We centred the hole 50mm below the centreline of the bowl see (Photo 5). This results in the port pointing upwards inside the Speaker.

You need to cut 10mm off the 25mm port to make it 90mm long; otherwise, it will interfere with the speaker magnet later. We made the hole tight enough that we had to push the port in forcefully. If your hole is too big, glue the port in using some acrylic filler.

Speaker connectors

We used very simple combo banana/binding posts. The speakers' power handling does not warrant anything massive, but we think these are better than the cheap spring-loaded terminals. The location of the connectors is largely a matter of convenience; ours are shown in Photo 5.

These need an 8mm hole, although we prefer to start smaller and use a file to get a good fit with the chamfered keying on the threaded section. That stops them from coming loose and spinning.

Our experience building the prototype showed that it is possible to solder to these terminals once they are in the assembled Speaker, but it is fiddly. We recommend you pre-install the input wiring to these terminals. Solder 300mm lengths of black and red wire to each pair and add 6mm diameter heatshrink tubing over the solder joints. You can trim the wires to length once you have attached them to the crossover.

Adding feet

As mentioned earlier, they need feet for desktop use. We used brass knobs because we thought they looked nice and were easy to fit. They are not individually that expensive, but there are six, so it does add up. You might come up with your own solution.

The feet are visible in Photos 5 & 6. They fit through 4mm holes drilled as shown in Fig.6. Whatever feet you choose, make sure you place them so the Speaker is stable; their placement must consider the centre of gravity being pulled forward by the weight of the driver magnet.

The knobs we used come with long bolts that you can cut and then file the ends smooth to ensure they thread onto the knobs without sticking. You can use a metal file to do that.

Gluing the pieces together

Sticking the two salad bowls together is as simple as it sounds. We used 120 grit sandpaper to take the gloss off the rim of the bowls and around the inside of the bowls. This ensures there is a good surface for the glue to adhere to.

We then mixed five-minute epoxy (Araldite), a teaspoon full or less per bowl. Use a piece of thin wire, 1mm in diameter or so, to apply a small bead around the top rim of the base bowl. Our tips are:

- Do not use too much glue, or it will ooze out around the joint.

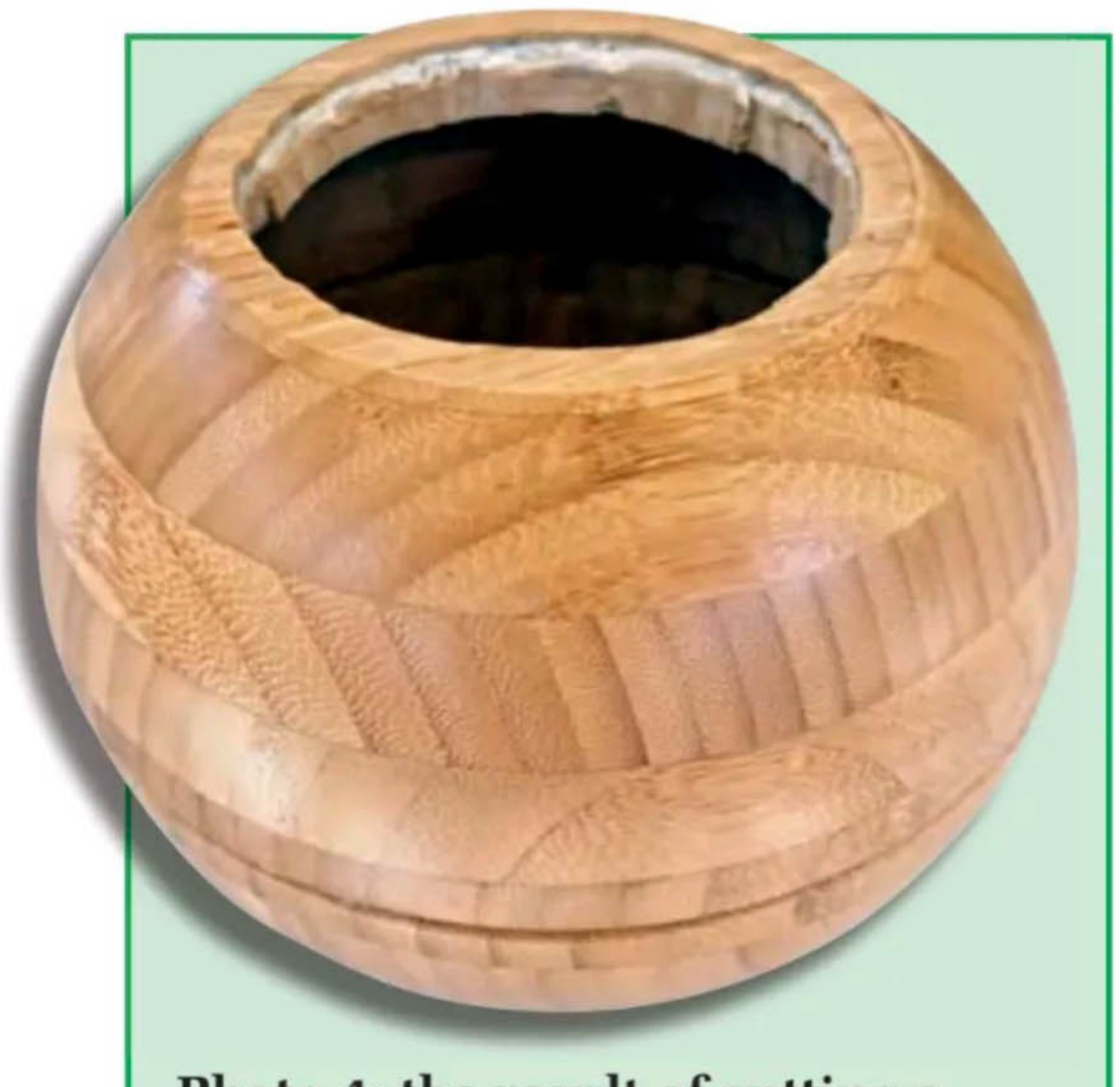


Photo 4: the result of cutting a 102mm diameter hole in both the base of the bowl (already routed to have a larger flat area) and the MDF reinforcement disc, leaving just a ring.

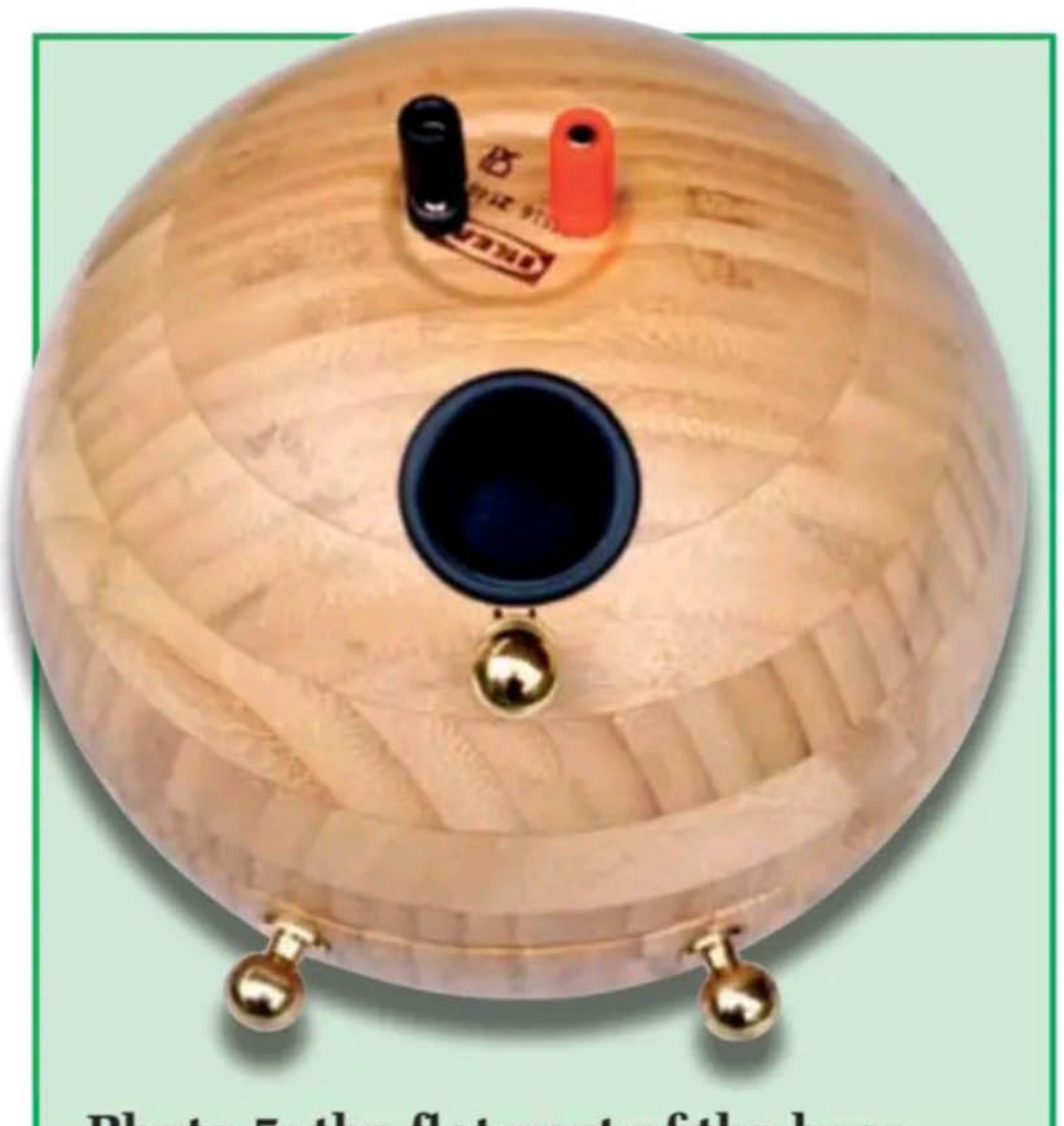


Photo 5: the flat part of the base opposite the driver cutout provides a place to mount the two binding posts, while the port is offset so it fires downwards and clears the internal crossover assembly.

Photo 6: the finished speakers look classy, if a bit unusual. Fans of post-modern art could paint them white and add red wiggly radial lines around the drivers to make them look like eyeballs!

- Get everything ready before you start applying the glue. It will set in less than five minutes, so you don't have time to muck around.
- Be ready to clean up spills; have cloths and isopropyl alcohol/white spirits ready.
- Know how you want to align the bowls. Ours were so random that we kind of gave up, but you might be more discerning than us.

Once you have a thin bead on the bottom bowl, gently place the top bowl over it. Very gently wriggle it to ensure both sides are wet, and check that everything is aligned. Set it aside for a while.

Once the main joint is set, mix another batch of glue and, using an icy pole stick or similar, run a bead of glue around the joint inside the glued bowls to ensure the final result is airtight. With the roughened surface, the epoxy bond will be extremely strong.

Assembling the crossover

The crossover PCB with chamfered corners is coded 01109231 and measures 98 × 104mm – see Fig.7.

We etched the PCBs shown in the photos ourselves as the design is simple. PCBs for sale will be the usual green commercial products, but otherwise identical to these.

Our photographs show yellow polypropylene 15µF capacitors, which are overkill; we simply used them as they were on hand. We have specified 15µF 100V bipolar electrolytic capacitors as they will work perfectly well and are what we would buy if building another pair of speakers.

We have left room for a 400µH inductor to be used in place of the recommended 250µH inductor. All testing was done with 250µH, but you can experiment; we don't expect much difference in performance over the range of 250µH to 400µH.

If you want to experiment, run wires from the drivers out through the port to the crossover. Get the crossover as you want before gluing it into the Speaker.

Assembly is straightforward. Fit the screw terminals first; still, you might want to simply solder flying leads and save on this cost. If you choose to do this, solder 300mm flying leads to the bass and tweeter connectors and label them so you know what goes where. The input wires should already be soldered to the input connectors.

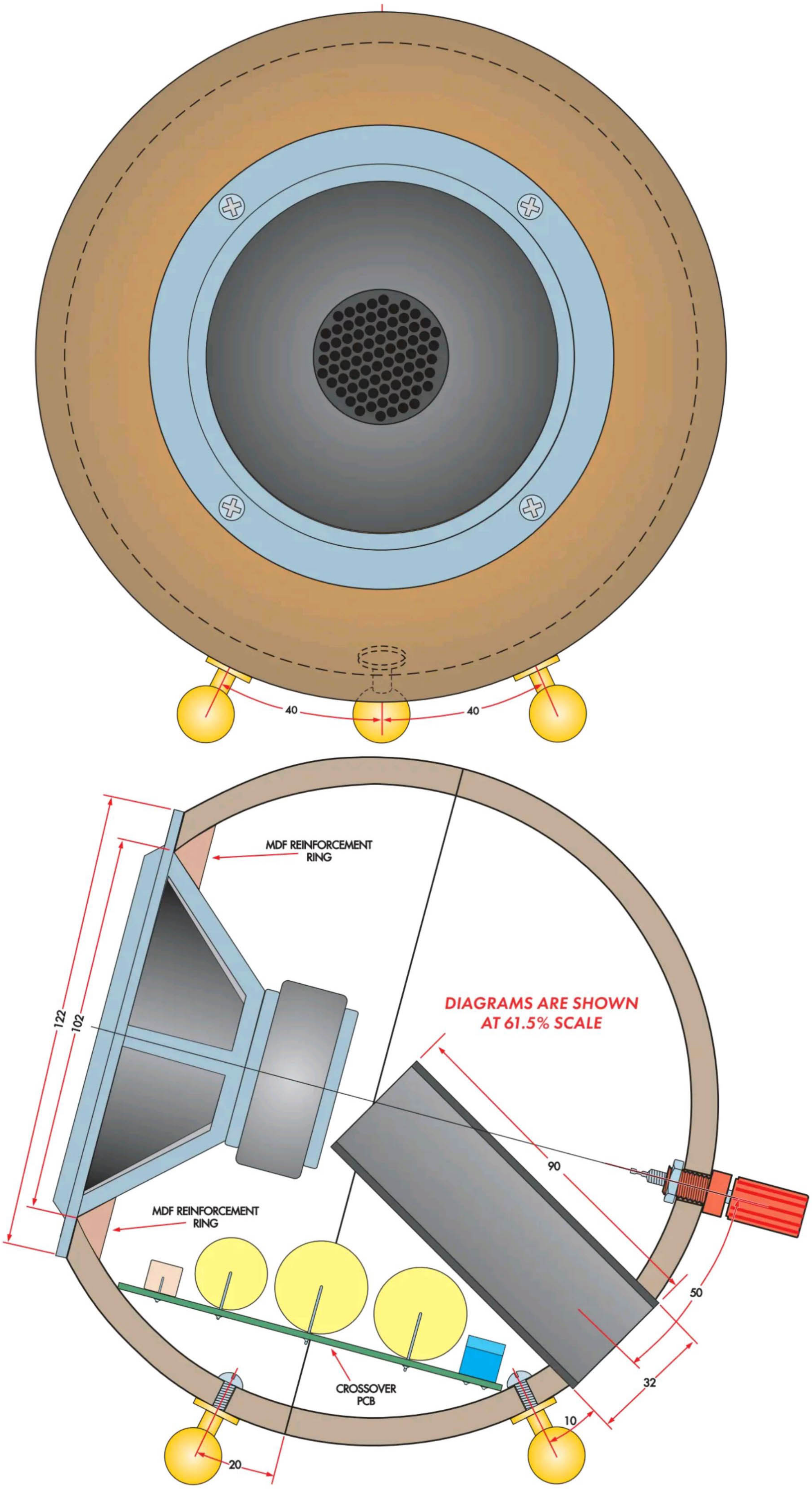


Fig.6: these views of an assembled Speaker should give you a good idea of the relative locations of the driver, feet, port, crossover and terminals. You could vary some of these slightly but we feel our design is pretty close to optimal.

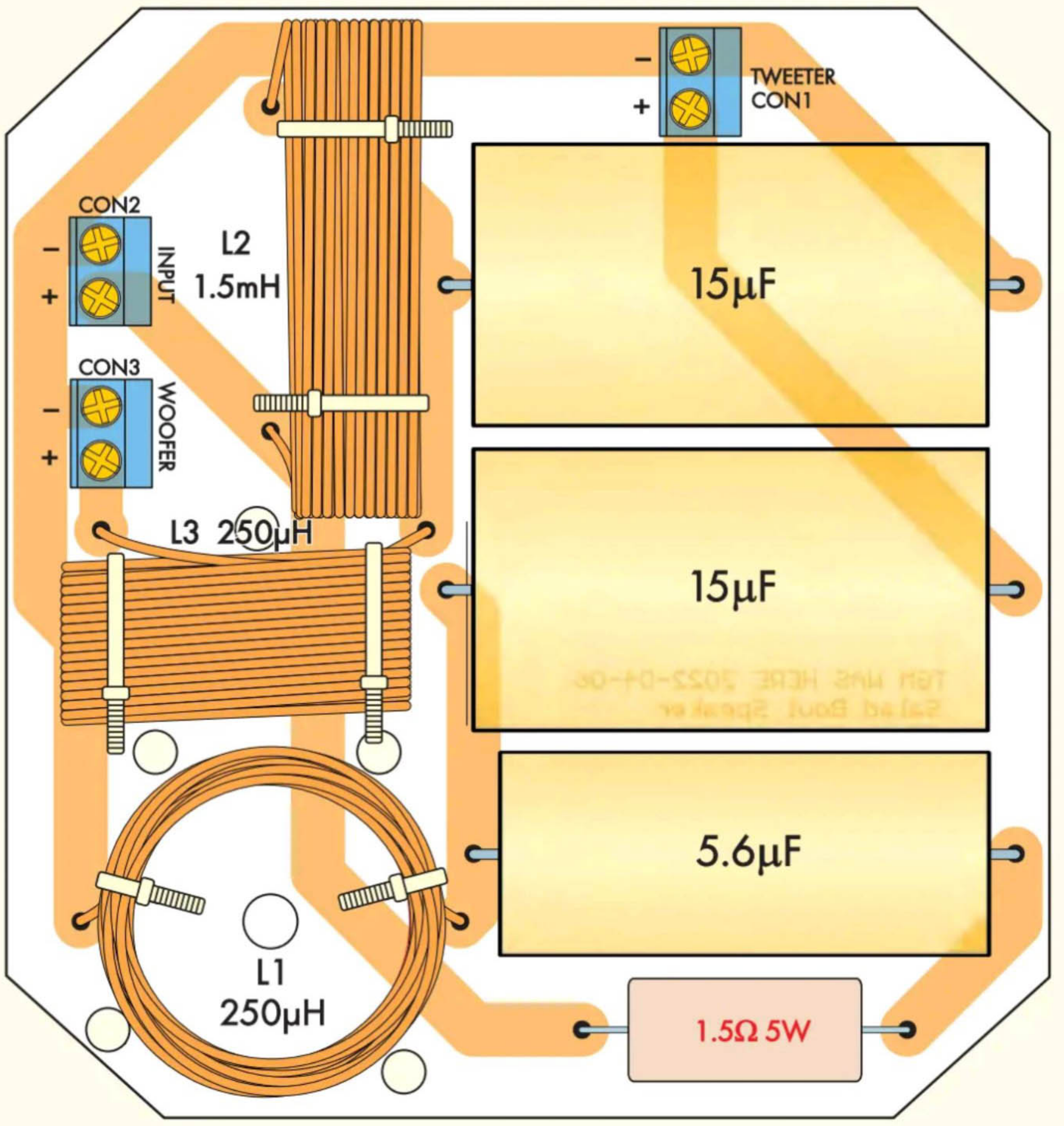
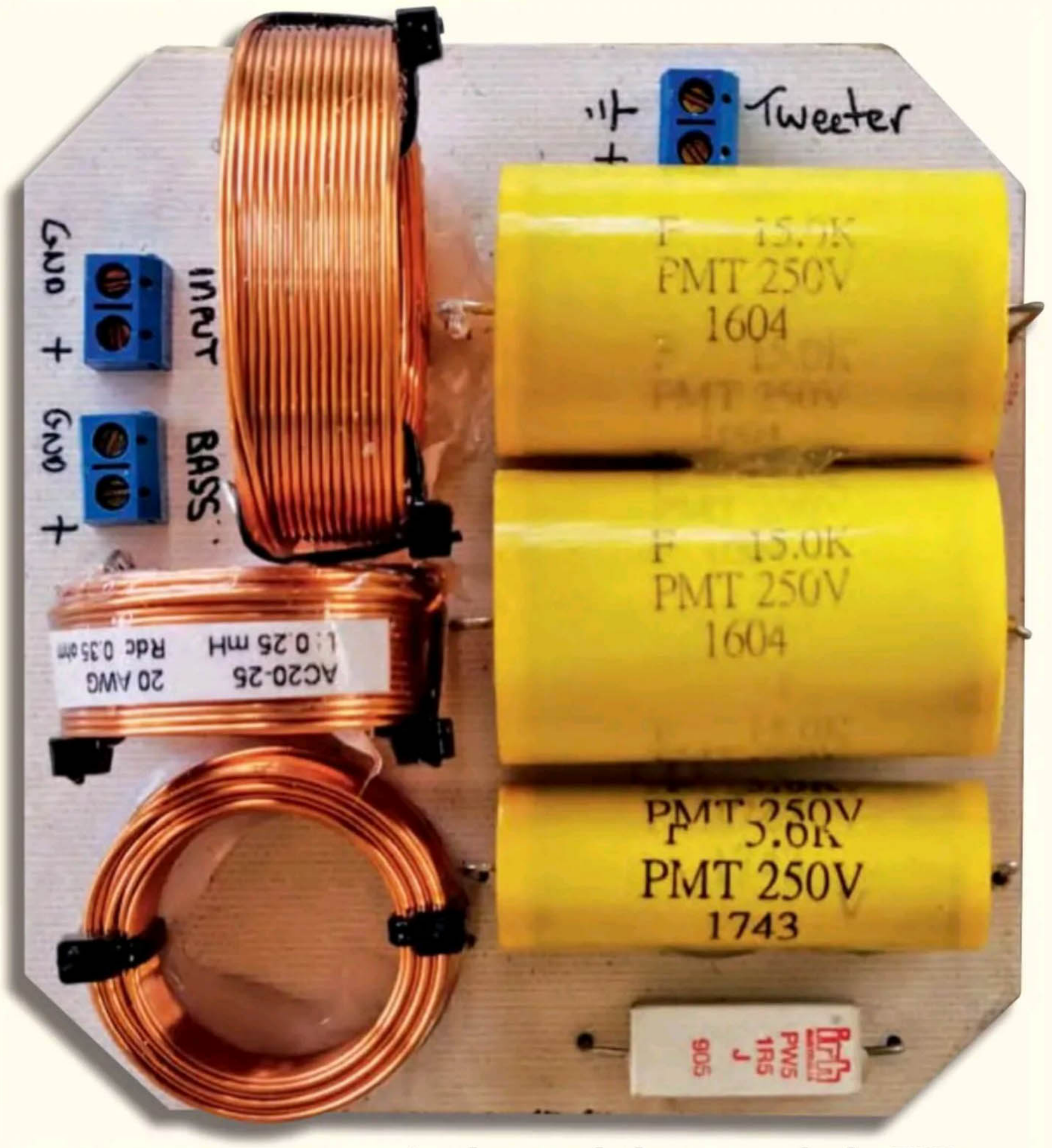


Fig.7: the crossover PCB is straightforward to assemble. While we're showing the capacitors as axial polyester types, axial crossover bipolar electrolytic capacitors are considerably cheaper, especially for the 15μF cap, and will work fine. Ensure the inductors are mounted as shown so their magnetic fields won't interact (much).



The prototype crossover was simple enough that we made the PCB ourselves. We recommend using electrolytic crossover capacitors instead of the two large 15μF polypropylene capacitors shown here.

Next, mount the resistor. This does not need to be proud of the PCB, as if this is getting hot, your tweeter will be in serious trouble. So it's OK to push it down flat before soldering and trimming the leads.

Install the capacitors next, none of which are polarised. Put a dab of neutral-cure silicone sealant under each to stop them from vibrating.

Finally, solder the inductors in place. Note that these are all at right angles to the others to ensure the magnetic fields don't interact. Make sure you stick to this arrangement. Again, glue each in place with a solid dab of neutral-cure silicone.

With all the components mounted, check your soldering and that everything is in the right place before moving on. Let the silicone cure before moving on to final assembly.

Final speaker assembly

Before you glue everything in place, let's check that everything works, as it is diffcult to remove the crossover afterwards. Do the following on the bench. Strip a short length of all the flying leads and connect the leads from the input connector to the input terminals.

Next, connect the bass driver and tweeter to their respective inputs on the crossover but connect only the ground wires at the driver end at this stage. We want to just touch the positive wire for the test. You can tell which is which as the bass driver connections have heavy-duty tinsel going into the spider on the driver while the tweeter connections run to thin wires going to the rear of the magnet assembly.

Apply a signal to the inputs and touch the positive bass wire to the terminal on the driver. You should only hear the lower-frequency parts of the test signal. It won't have any real bass with the driver on the bench.

If you hear treble instead, or nothing, check your connections.

Next, touch the tweeter positive wire to the terminal on the speakers. You should hear 'hissy' treble. It will not be loud. If there is nothing or all you hear is muted sound, check your wiring and component values.

Assuming that it all checks out, test-fit the crossover into the enclosure. Photo 7 provides a pretty good view of how to install it. You need to align the thin axis with the hole

Parts List – Salad Bowl Speakers

Pair of desktop speakers

2 SB Acoustics 120mm coaxial speakers
[Willys-HiFi Ltd SB12PFCR25-4-COAX]
2 25mm diameter, 100mm-long PortBASS reflex ports
[Willys-HiFi Ltd FL28-102]
4 IKEA salad bowls
[BLANDA MATT 20cm bamboo serving bowl, 002.143.41]
2 16mm MDF sheets or off-cuts, at least 120×120mm each
2 red captive head binding posts for speaker terminals **[Altronics P9252]**
2 black captive head binding posts for speaker terminals **[Altronics P9254]**
6 ~15mm brass doorknobs for feet
3 2m lengths of heavy-duty hookup wire (white/blue, black and red)
1 100mm length of 6mm diameter heatshrink tubing
8 6G × 20mm countersunk head wood screws (ideally black)
2 400 × 150mm (approx.) pieces of 50mm-thick acrylic wadding or similar
1 small tube of 5-minute epoxy **[eg, Araldite]**
1 310ml tube of White SikaSeal Acrylic 100 Gap Filler
2 crossover boards (see below)

Crossover board – parts to build one board

1 single-sided PCB coded 01109231, 98 × 104mm
2 250-270µH air-cored crossover inductors (L1, L3)
[Willys-HiFi Ltd 1340230]
1 1.5mH air-cored crossover inductor (L2) **[Willys-HiFi Ltd 1700511]**
2 15µF 100V non-polarised electrolytic crossover capacitors
[Willys-HiFi Ltd MKTA-150]
1 5.6µF 100V metallised polypropylene crossover capacitor
[Willys-HiFi Ltd 1341866]
3 dual mini terminal blocks, 5.08mm pitch (**optional**; CON1-CON3)
1 1.5Ω 5W 5% resistor (can be varied to adjust treble balance; see text)

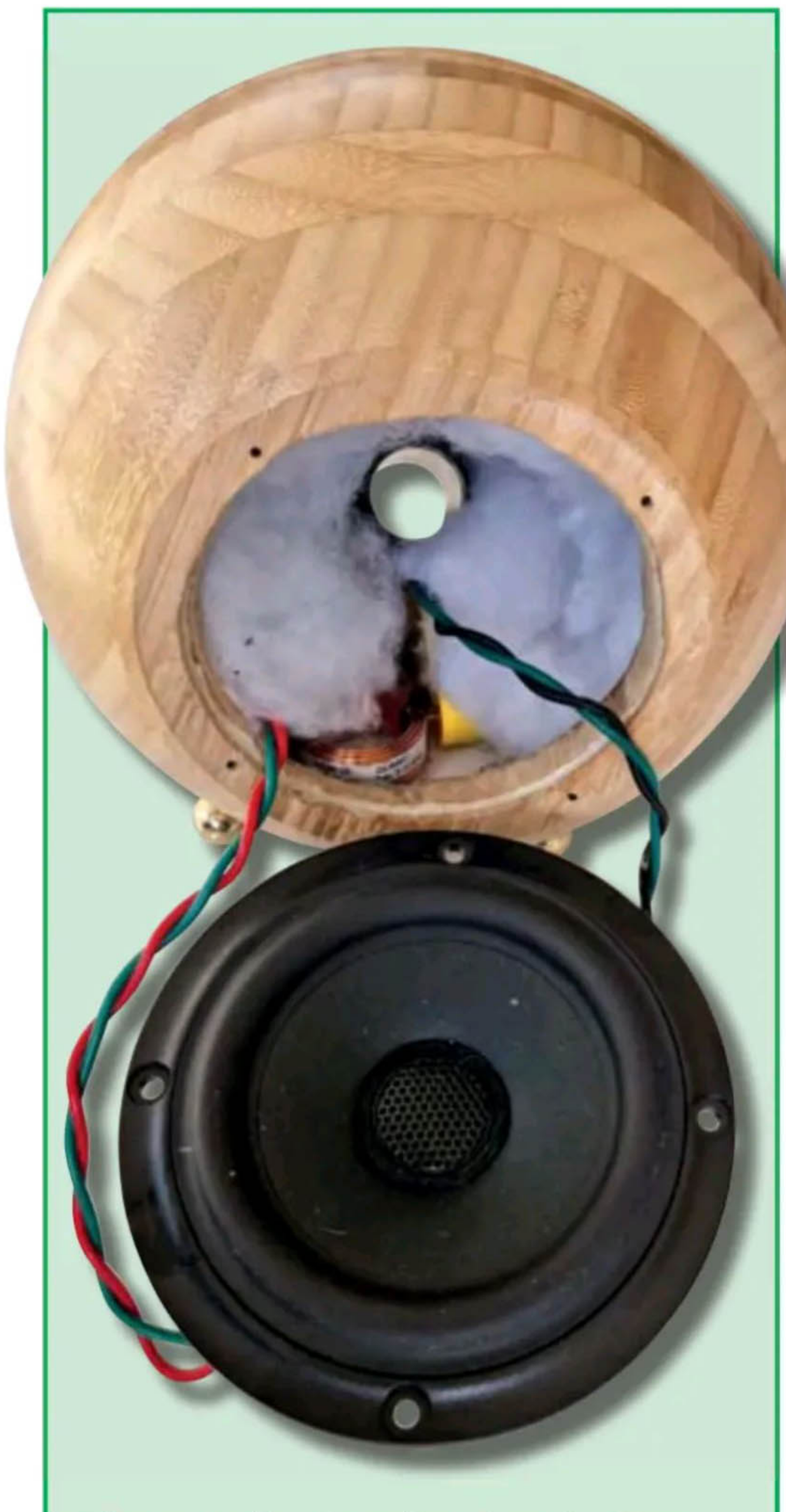


Photo 8: the Speaker just before we finally attached the driver, with acoustic wadding loosely stuffed inside.

and put the 1.5mH inductor in first, as we need this at the back to make room. We also need the weight at the back to improve the balance of the Speaker.

Once you are sure you know how you will get things in and out and that there is room (fettle the hole if necessary), we are set to finalise the wiring.

Trim the input and output wires so that, with the driver in front of the enclosure, you have sufficient length for the crossover to be glued in place. Solder the connections for the bass, tweeter and input. It is important to put some 6mm heatshrink on the speaker terminals when you connect the wires. These terminals are close to the crossover, and we do not want them shorting to it.

Now put solid dabs of neutral-cure silicone sealant on the underside of the PCB at each of the rounded corners. Then install the board, with some tissues/rags handy to clean your fingers. Carefully insert the crossover into the Speaker enclosure. As you will have found, it is a little like a puzzle, but it does go in and sits alongside the port.

Make sure there is silicone still under the PCB, and where you inevitably rub some onto the enclosure, clean up immediately.

We used a long screwdriver to add some extra silicone between the enclosure wall and the top of each corner of the PCB to ensure it won't move later.

Leave it to cure; don't be tempted to rush this, as silicone has no strength until it cures. We used a small piece of leftover acrylic wadding as damping for the Speaker, as shown in Photo 8.

Anything like open-cell foam, acrylic wadding or the contents of a disused cushion would do. Lightly stuff the enclosure and ensure the port is not completely blocked. Now where did that cushion go?

Finally, install the driver. We mounted the driver with the terminals horizontal. This ensures that the terminals cannot rub against the crossover components.

Ensure each driver has the same rotation so the screws line up. They will look silly if the screws are all over the place. We drilled a 1.5mm pilot hole for each screw and used 6GA wood screws. Do these 'gently hand tight'. These simply need to secure the driver well enough to achieve an air seal.

Testing and setup

Now for the fun! You will note that

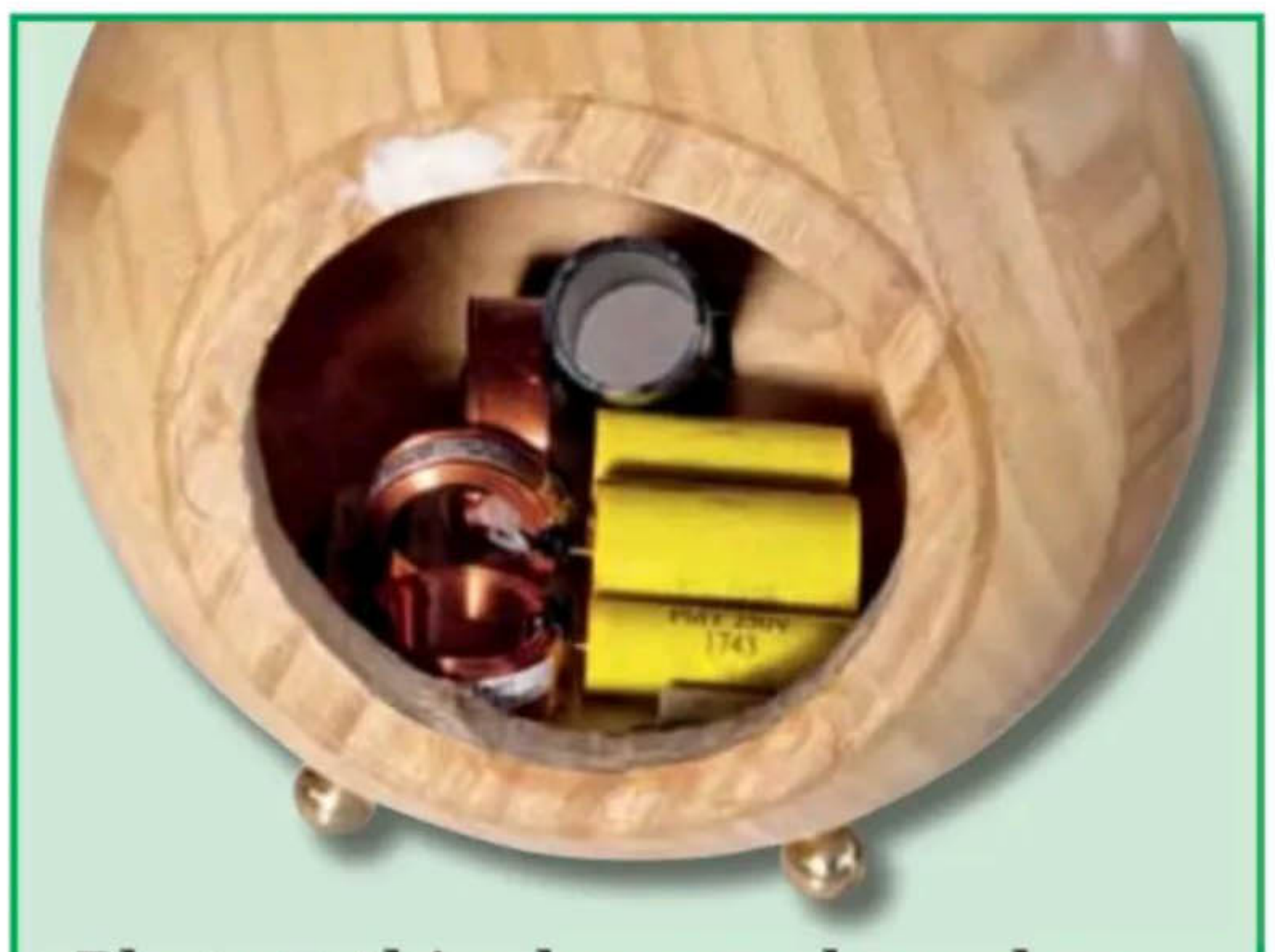


Photo 7: this close-up shows how the crossover board is orientated so the closest inductor just misses the port tube.

The Salad Bowl Speaker (not shown at actual size).

the acoustic output is night and day between the driver on the bench and in the enclosure. We were surprised at the bass output these little speakers deliver.

Start gently and play some program material, verifying that there is output from the tweeters and bass drivers. If there is anything odd, now is the time to check. Once everything is good, you are set to find where to put them!

Often you have little discretion in the placement of a speaker. Try to find a spot with free space around and behind the Speakers. We found that when placed right up against a wall/desk junction, there was a reinforcement of bass, with a pronounced peak in the bass region. As mentioned earlier, blocking the port(s) should reduce that.

Refrain from facing the speakers straight at your listening position, though this is less of a concern on a desk. The crossover is optimal for a slightly offset listening position.

Observations

Our most ardent critic at home loves the style. We think it is interesting, both visually and in terms of a speaker free from diffraction, and we see this in the plots.

The coaxial driver really met our expectations, with a consistent sound experience at a wide range of angles.

The low end surprised us. It is not a disco speaker but does a fine job for moderate listening. As the measurements suggest, the sound is clean and free from annoying characteristics.

We could hear the elevated bass when we used the Speaker in a corner, so we would use no port in such a location.

While we have rated them at 50W, you should show some discretion if playing deep bass through them. These are intended for small rooms, on computer desks and similar.

While the impedance is nominally 4Ω, they present a fairly benign load with a higher-than-rated impedance over most of the audio range. Any modern amplifier will happily drive them. Our inexpensive, compact Hummingbird amplifier module is ideal (see the December 2022 issue). PE

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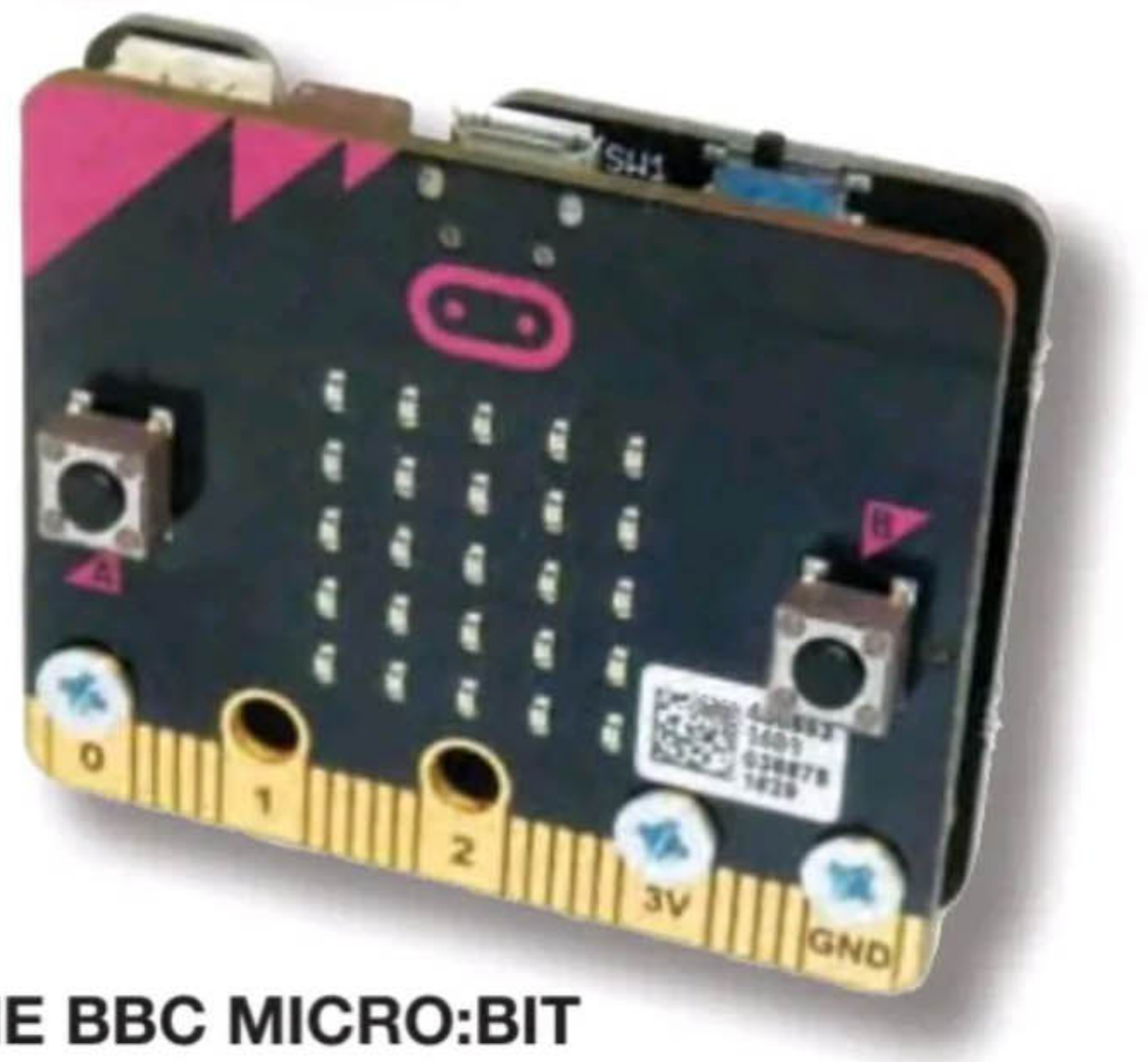
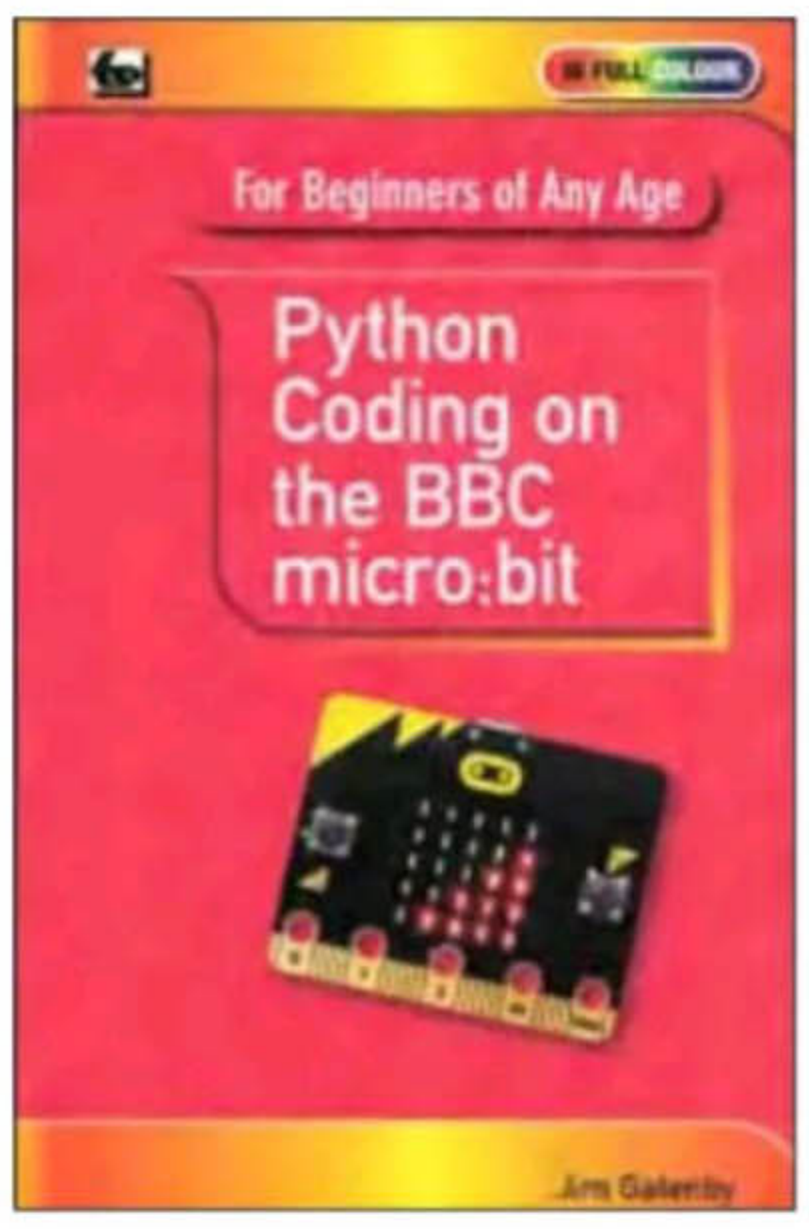
Teach-In 2017

Introducing the BBC micro:bit





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Jim Gatenby

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This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

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Mike Tooley

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Teach-In 2024

Learn electronics with the ESP32

by Mike Tooley

Part 7 – Telling the Time

ESP-WROOM-32
EN
BOOT

In the last part of our *Teach-In* series, we explored some of the ESP32's inbuilt features that make wireless communication a reality. That started with a simple wireless Access Point to send environmental data that can be displayed on a phone, tablet, laptop or desktop PC.

This instalment continues that theme by showing how an ESP32 can connect to the Internet and use a network time protocol (NTP) server to obtain the current time with very high accuracy.

Our *Practical Project* features the construction of a highly accurate digital clock with a low-cost 16 × 2 LCD panel display, while our *Coding Workshop* will take your coding skills to a new level by introducing arrays and structures.

The learning objectives for the seventh part of our series are:

- Know how to connect to an NTP time server
- Know how to format and display NTP data
- Know how to use C++ arrays and structures

The Network Time Protocol (NTP)

The Network Time Protocol is a set of rules for synchronising computers and microcontrollers using data derived from a standard network time reference. This allows you to obtain the time and date with very high precision and without any additional hardware.

NTP servers (see Table 7.1) must operate independently of their locale, providing worldwide access to UTC (Universal Coordinated Time).

Like GMT (Greenwich Mean Time), UTC is the same all over the world and needs to be adjusted for the local time zone and daylight saving, where appropriate.

To use NTP with an ESP32 (or similar microcontroller), we usually configure the ESP32 as a client that connects to an NTP server via the UDP (User Datagram Protocol) on port 123. Once connected, the client sends a request packet to the server, which responds with a timestamp packet containing data that's parsed to extract the required information.

Using the public Internet, NTP usually maintains time to within just a few milliseconds, but when used in the more controlled environment of a LAN (Local Area Network), the accuracy can be improved to within 1ms.

Unlike protocols like TCP, UDP does not rely on handshaking and does not keep track of what's sent. It thus avoids the repeat transmissions and overheads associated with error checking, and is the preferred method for time-critical applications like NTP.

Table 7.1 – Internet time servers

Region	Host name
Asia	asia.pool.ntp.org
Europe	europe.pool.ntp.org
North America	north-america.pool.ntp.org
Oceania	oceania.pool.ntp.org
South America	south-america.pool.ntp.org
Worldwide	pool.ntp.org

About Teach-In

Our latest *Teach-In* series is about using the popular ESP32 module as a basis for learning electronics and coding. We will be making no assumptions about your coding ability or your previous experience of electronics. If you know one but not the other, you have come to the right place. On the other hand, if you happen to be a complete newbie there's no need to worry because the series will take a progressive hands-on approach. There will be plenty of time to build up your knowledge and plenty of opportunity to test things out along the way.

We've not included too much basic theory because this can be easily found elsewhere, including several of our previous *Teach-In* series, see:

https://bit.ly/pe-ti
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Earch month, there'll be projects and challenges to help you check and develop your understanding of the topics covered.

Time zones

To compensate for different time zones, it is necessary to adjust the UTC offset. This is calculated by multiplying the GMT zone by 3600 (the number of seconds for each hour difference in GMT).

This is quite easy to do, as illustrated by the time zone and daylight saving offsets for various cities in Table 7.2.

For example, the GMT offset for Paris is `gmtOffset_sec = 3600` while that for Singapore is `gmtOffset_sec = 28800`. In our code, each of these time zone offsets would be defined as longs using lines like these two examples:

```
const long gmtOffset_sec = 3600; // Paris
const long gmtOffset_sec = 28800; // Singapore
```

Gotcha!

Because UTC and GMT share the same current time, they are often confused. The essential difference between the two is that UTC is a time standard while GMT is a time zone that just happens to have zero offset from UTC.

Daylight saving time (DST)

First proposed by Benjamin Franklin in Paris in 1784, daylight saving is the practice of putting clocks backwards in winter and forwards in summer to make best use of the available daylight. Today, many countries observe this practice, so it must be accommodated when obtaining local times from UTC.

To obtain the time adjusted for daylight saving, we use a further one-hour offset which is applied during the applicable months.

Since we are only dealing with an offset of 3600 seconds, we can use an integer value with a line of the form:

```
const int daylightOffset_sec = 3600; // DST offset
```

Having determined the required time zone and DST offsets, we are ready to configure the application using the values that we have defined. This can be achieved using the timeconfigTime() function, as follows:

```
timeconfigTime(gmtOffset_sec,
                 daylightOffset_sec, ntpServer);
```

Check it out!

The time has come to check out your ESP32's ability to obtain and display NTP data, so let's connect to the default (worldwide) NTP time server, retrieve the current time and display it using the Serial Monitor. That might sound complicated, but it's actually quite easy!

We need to include two required libraries, <WiFi.h> and "time.h", using:

```
#include <WiFi.h>
#include "time.h"
```

The first of these two libraries manages the ESP32's Wi-Fi interface while the second facilitates the exchange of data between the ESP32 (as a client) and the NTP time server.

Next, we will need to define various network parameters including the SSID (see last month), Wi-Fi password, NTP time server and the required offsets for GMT (time zone) and DST. You may have a different offset, but for London (UK), this is achieved using code like:

```
// Network parameters
const char* ssid = "YOUR_SSID";
const char* password = "YOUR_PASSWORD";
const char* ntpServer = "pool.ntp.org";
const long gmtOffset_sec = 0;
const int daylightOffset_sec = 3600;
```

The getLocalTime() function will send a request packet to the NTP server, parse the time stamp packet received, and store the date and time information extracted from it in a time structure called timeinfo.

There will be more information about the use of C++ structures is in the Coding Workshop below, under the heading *Coding Workshop* on page 72.

The complete code listing appears in Listing 7.1, while Fig.7.1 is a screen grab showing how the data appears in the ESP32's Serial Monitor.

Table 7.2 – Time zones and DST offsets for various cities

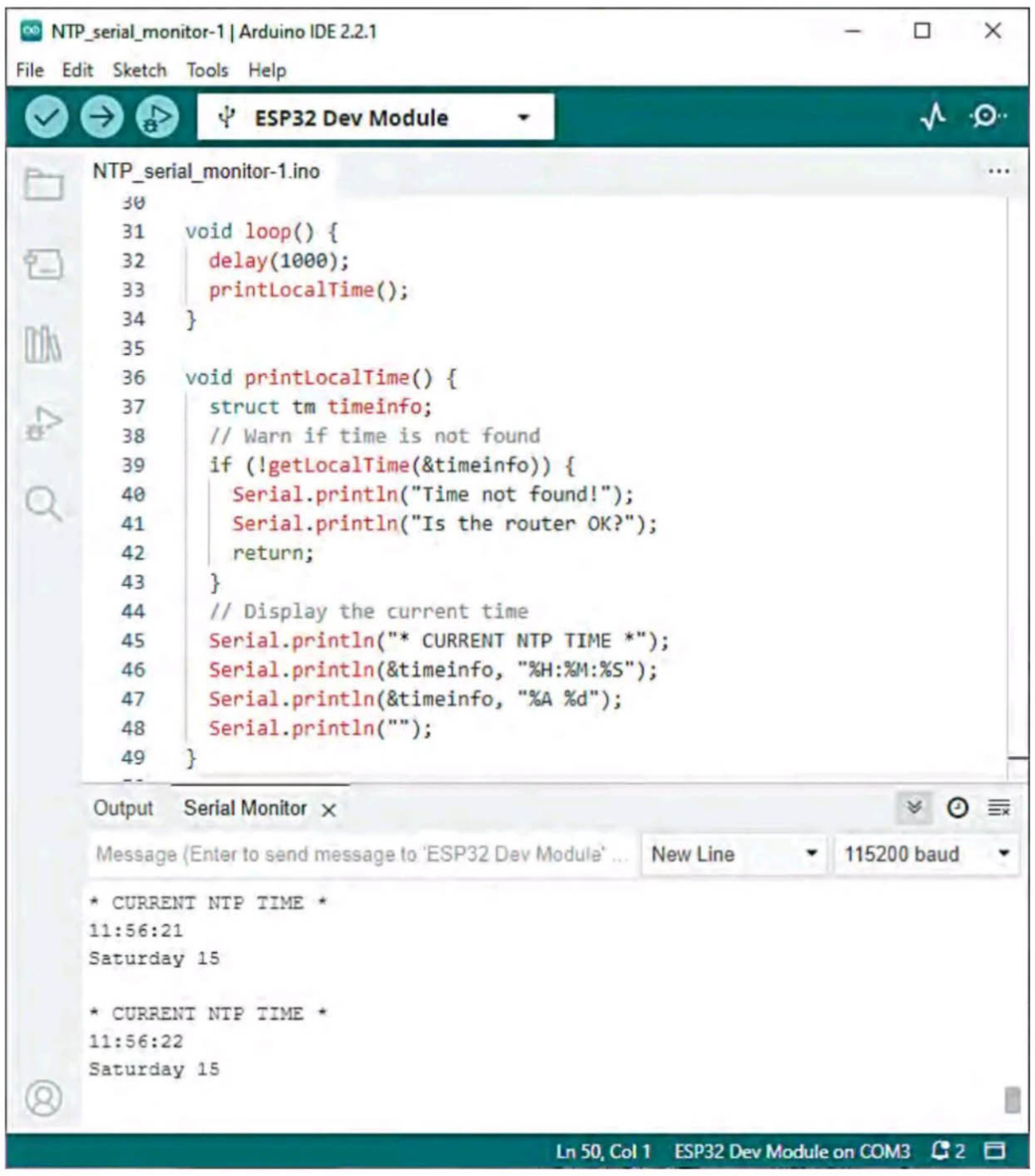
City & country	Time zone	Offset	DST?
Adelaide, Australia	GMT+9½	9.5 × 3600 = 34200	Yes
Athens, Greece	GMT+2	2 × 3600 = 7200	Yes
Brisbane, Australia	GMT+10	10 × 3600 = 36000	No
Helsinki, Finland	GMT+2	2 × 3600 = 7200	Yes
London, England	GMT+0	0 × 3600 = 3600	Yes
New York, USA	GMT−5	−5 × 3600 = −18000	Yes
Paris, France	GMT+1	1 × 3600 = 3600	Yes
Singapore	GMT+8	8 × 3600 = 28800	No

Listing 7.1 – Fetch and display NTP time data using the ESP32's Serial Monitor

```
// Include the required library files
#include <WiFi.h>
#include "time.h"

// Network parameters
const char* ssid = "YOUR_SSID";
const char* password = "YOUR_PASSWORD";
const char* ntpServer = "pool.ntp.org";
const long gmtOff_sec = 0;   // Change if necessary
const int daylightOff_sec = 3600;  // Change if nec.

void setup() {
  Serial.begin(115200);
  // Connect to Wi-Fi
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
   }

  // Initialise and get the time
  configTime(gmtOff_sec, daylightOff_sec, ntpServer);
  printLocalTime();

  // Disconnect WiFi
  WiFi.disconnect(true);
  WiFi.mode(WIFI_OFF);
}

void loop() {
  delay(1000);
  printLocalTime();
}

void printLocalTime() {
  struct tm timeinfo;
  // Warn if time is not found
  if (!getLocalTime(&timeinfo)) {
    Serial.println("Time not found!");
    Serial.println("Is the router OK?");
    return;
  }
  // Display the current time
  Serial.println("* CURRENT NTP TIME *");
  Serial.println(&timeinfo, "%H:%M:%S");
  Serial.println(&timeinfo, "%A %d");
  Serial.println("");
}
```

Gotcha!

The default NTP time server at **pool.ntp.org** automatically selects a time server that is nearby, but you can specify a different time server selected from the list in Table 7.1. You may also need to change one or both offsets as required for your location.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New Line
115200 baud
Ln 50, Col 1
ESP32 Dev Module on COM3

```
void loop() {
  delay(1000);
  printLocalTime();
}

void printLocalTime() {
  struct tm timeinfo;
  // Warn if time is not found
  if (!getLocalTime(&timeinfo)) {
    Serial.println("Time not found!");
    Serial.println("Is the router OK?");
    return;
  }
  // Display the current time
  Serial.println("* CURRENT NTP TIME *");
  Serial.println(&timeinfo, "%H:%M:%S");
  Serial.println(&timeinfo, "%A %d");
  Serial.println("");
}
```

```
* CURRENT NTP TIME *
11:56:21
Saturday 15

* CURRENT NTP TIME *
11:56:22
Saturday 15
```

Fig.7.1: The output of the ESP32 Serial Monitor running the NTP sketch in Listing 7.1.

Working with time data

A wide variety of options can be used to extract the data that you need from the timeinfo structure. This makes it delightfully easy to manipulate and format the data that you need. Table 7.3 lists the available specifiers.

For example, %A is used to obtain just the day of the week while %F will provide you with the data in long (YYYY-MM-DD) format.

The code fragment in Listing 7.2 shows just a few of the formatting option for date/time strings. The result of running the code is shown in Fig.7.2.

Coding Workshop

This month's Coding Workshop provides you with an introduction to the arrays and structures available in C++.

Listing 7.2 – Some possible date/time string formats

```
// Display current time in different formats
  Serial.print("Formatted time: \t");
  Serial.println(&timeinfo, "%T");
  Serial.print("Time (24 hour format): \t");
  Serial.println(&timeinfo, "%R");
  Serial.print("Time (12 hour format): \t");
  Serial.println(&timeinfo, "%r");
  Serial.print("Minutes and seconds: \t");
  Serial.println(&timeinfo, "%M:%S" );
  Serial.print("Month, day and year): \t");
  Serial.println(&timeinfo, "%B %d %Y");
  Serial.print("Date (long format): \t");
  Serial.println(&timeinfo, "%F");
  Serial.print("Date (short format): \t");
  Serial.println(&timeinfo, "%D");
  Serial.print("AM or PM: \t\t");
  Serial.println(&timeinfo, "%p");
  Serial.print("Day of the year: \t");
  Serial.println(&timeinfo, "%j");
  Serial.println("");
```

Table 7.3 – Parsed values returned by getLocalTime()

Specifier	Value returned	Example
%A	Day of the week	Monday
%a	Day of the week (abbreviated)	Mon
%B	Month of the year	January
%b	Month of the year (abbreviated)	Jan
%D	Short format date (MM/DD/YY)	05/15/24
%d	Day of the month	12
%F	Long format date (YYYY-MM-DD)	2024-02-10
%H	Hour of the day (24-hour format)	21
%I	Hour of the day (12-hour format)	9
%j	Day of the year	211
%Y	Year	2024
%y	Last two digits of the year	24
%m	Month as a number	05
%M	Minute of the hour	59
%p	AM or PM	PM
%r	12-hour clock time	09:15:21 am
%R	24-hour time HH: MM	21:19
%S	Second of the minute	21
%T	Formatted time (HH: MM: SS)	09:15:21

Arrays provide a way of storing multiple values within a single variable, avoiding the need for separate variable declarations.

Structures take this one stage further by allowing you to group variables regardless of their type. Let's see how they work.

String arrays

We briefly mentioned string arrays in Part 6 of this Teach-In series, when we showed how strings are stored as an array of alphanumeric characters.

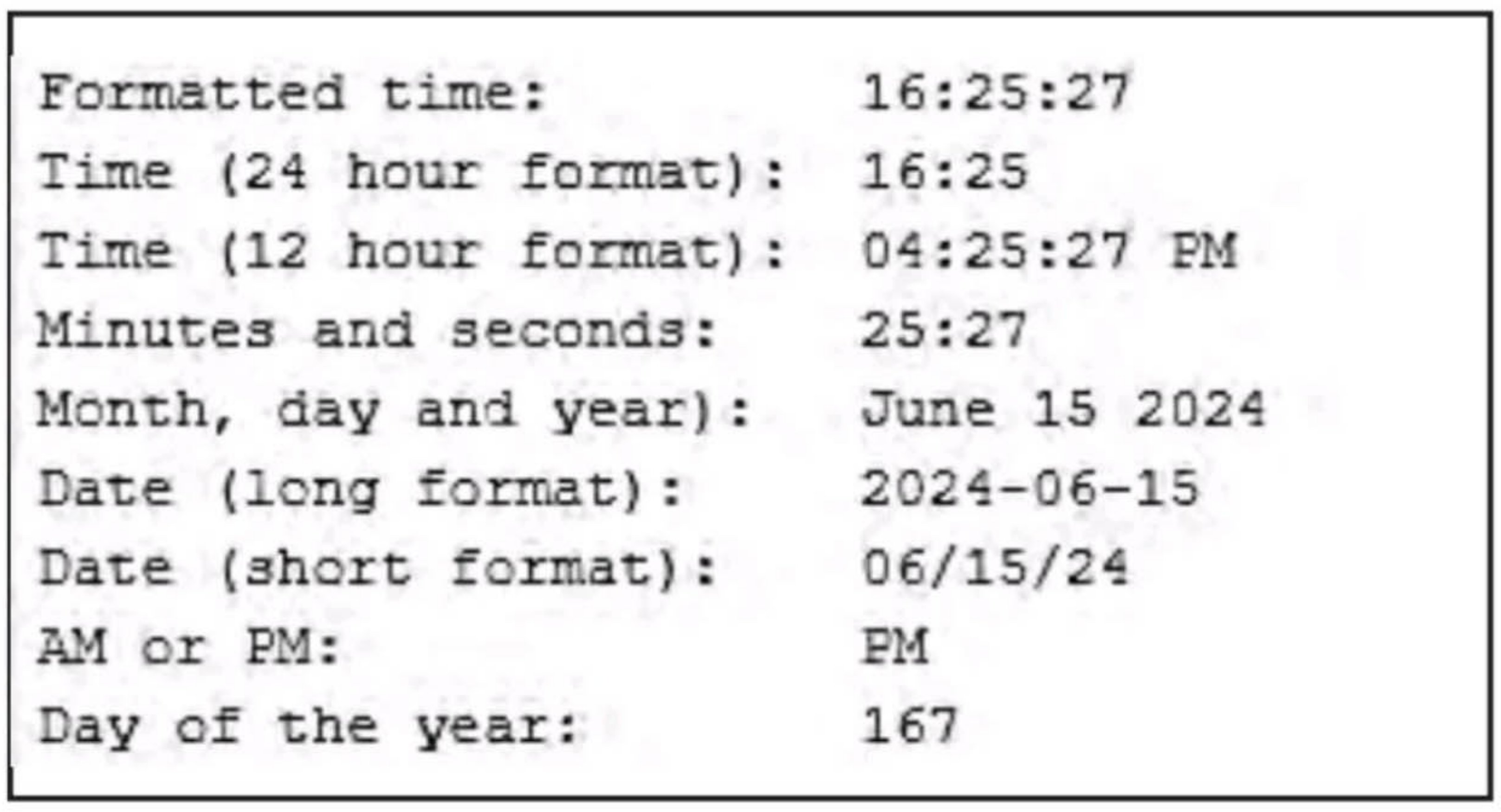
Arrays can be extremely useful, particularly when storing and manipulating the same data types.

To declare an array, you simply need to define the variable type, specify the name for the array and the number of elements that need to be stored. It is possible to have multi-dimensional arrays, but we'll stick to a single dimension here.

Note that the name of the array should be immediately followed by square brackets containing the number of items in the array. Here are two examples:

```
string colourChannel[5];
```

This declares a colourChannel[] array that will hold six string



```
Formatted time:          16:25:27
Time (24 hour format):   16:25
Time (12 hour format):   04:25:27 PM
Minutes and seconds:     25:27
Month, day and year):    June 15 2024
Date (long format):      2024-06-15
Date (short format):     06/15/24
AM or PM:                PM
Day of the year:         167
```

Fig.7.2: The result of running the code in Listing 7.2.

Gotcha!

Array indexes start with 0 so that [0] is the first element, [1] is the second element, and so on. It's important to remember this if you're coding with arrays!

variables. To place values into the array, we can arrange them in the form of a comma-separated list enclosed by a pair of curly braces:

```
string colourChannel[5] = {"Red", "Green", "Blue",
                           "Black", "White"};
```

Each string in the list is enclosed in its own opening and closing quotation marks. Without these, they won't be interpreted as strings!

Numeric arrays

Numerical values are handled similarly. For example, the following code fragment creates an array of four longs (32-bit or 64-bit integers) designed for use in the RF synthesiser of an FT8 HF transceiver:

```
long txFT8[4] = { 3573000, 7074000, 10136000,
                  14074000 };
```

Accessing array elements

Individual elements stored within an array are accessed using an index number with a value from 0 to one less than the size of the array.

This can be a little confusing, so we've provided some examples in Tables 7.4 and 7.5 which respectively show how the variables in our two previous array examples are indexed.

Structures

Structures, like those that we met earlier using NTP, provide a neat and efficient way of grouping related variables. However, unlike arrays, structures can contain a mixture of many different data types. In contrast, all the elements in a single array must be of the same type.

Each of the variables becomes a member of the structure. To create a structure, use the struct keyword and then declare each of its members, as shown in Listing 7.3.

In Listing 7.3, the sensors structure has seven members of which two are strings (name and type), two are integers (address and calibration), one is a long (data), and one is a Boolean (status).

Each of the sensors (Sensor1, Sensor2 and Sensor3) shares the same structure.

The variables that apply to the individual sensors are defined and initialised in the code, starting with Sensor1 and ending with Sensor3.

To show how the structure might be used, the loop included in the listing has some sample data for display using the ESP32's Serial Monitor.

Table 7.4 – Indexing the colourChannel[] array

Array index	Code reference	String stored
0	colourChannel[0]	Red
1	colourChannel[1]	Green
2	colourChannel[2]	Blue
3	colourChannel[3]	Black
4	colourChannel[4]	White

Listing 7.3 – Example of using data structures with the ESP32

```
/* Using structures with the ESP32 */

// Declare our structure
struct sensors {
  String name;                // Sensor name
  String type;                // Sensor type
  int address;                // Bus address
  bool status;                // Status flag
  int calibration;            // Calibration factor
  long data;                  // Sensor data
} Sensor1, Sensor2, Sensor3;  // Three sensors

void setup() {
  Serial.begin(115200);

  // Define the first sensor
  Sensor1.name = "Lobby";  // Lobby sensor
  Sensor1.type = "72X121";
  Sensor1.address = 64;
  Sensor1.status = false;
  Sensor1.calibration = 255;
  Sensor1.data = 0;

  // Define the second sensor
  Sensor2.name = "Hall";  // Hall sensor
  Sensor2.type = "72X121";
  Sensor2.address = 64;
  Sensor2.status = false;
  Sensor2.calibration = 127;
  Sensor2.data = 0;

  // Define the third sensor
  Sensor3.name = "Office"; // Office sensor
  Sensor3.type = "92Y200";
  Sensor3.address = 64;
  Sensor3.status = false;
  Sensor3.calibration = 192;
  Sensor3.data = 0;
}

void loop() {
  // Code to fetch and process sensor data goes here
  Sensor1.status = true;   // Sensor OK
  Sensor2.status = false;  // Faulty sensor detected
  Sensor3.status = true;   // Sensor OK
  // But for test purposes add some data here
  Sensor1.data = 12928;
  Sensor2.data = 0;        // No data returned
  Sensor3.data = 22491;
  // Check each sensor and if online display its data
  Serial.println("Current sensor data: ");
  if (Sensor1.status == true) {
    Serial.println(Sensor1.name + "\t" + Sensor1.data);
  } else {
    Serial.println(Sensor1.name + "\tFault!");
  }
  if (Sensor2.status == true) {
    Serial.println(Sensor2.name + "\t" + Sensor2.data);
  } else {
    Serial.println(Sensor2.name + "\tFault!");
  }
  if (Sensor3.status == true) {
    Serial.println(Sensor3.name + "\t" + Sensor3.data);
  } else {
    Serial.println(Sensor3.name + "\tFault!");
  }
  Serial.println();
  delay(5000);  // Wait five seconds
}
```

Table 7.5 – Indexing the txFT8[] array

Array index	Code reference	Numeric value stored
0	txFT8[0]	3573000
1	txFT8[1]	7074000
2	txFT8[2]	10136000
3	txFT8[3]	14074000

A Practical Project

Our *Practical Project* uses NTP to convert the ESP32 into a network-synchronised clock with the current time displayed on a low-cost 16 × 2 LCD panel.

The circuit to interface the ESP32 to the 16 × 2 LCD panel is shown in Fig.7.3.

The LCD panel is fitted with an I^2C interface (see Part 5) that only requires four connections: GND, VCC, SDA (I^2C data) and SCL (I^2C clock).

To centre the time on the LCD display, so that it looks nice, we need to be able to address individual character cells, as shown in Fig.7.4.

For example, after first initialising the LCD screen, to place the letter 'A' in row 0, column 9 of the display we would use the following code:

```
lcd.setCursor(9, 0);  // Cursor to row 0, column 9
lcd.print("A");       // Display the character
```

Whereas, to display the letter B in row 1, column 5, we use:

```
lcd.setCursor(5, 1);  // Cursor to row 1, column 5
lcd.print("B");       // Display the character
```

On each occasion, we've used lcd.setCursor to locate the character cell before printing the character.

The preferred layout for the date and time display is shown in Fig.7.5.

The starting point for the hours, minutes and seconds string is set to row 0, column 4, while the day and date appear below, starting at row 1, column 4.

The prototype layout for the network-synchronised clock is shown in the photo below, while the code for the ESP32 NTP clock is shown in Listing 7.4.

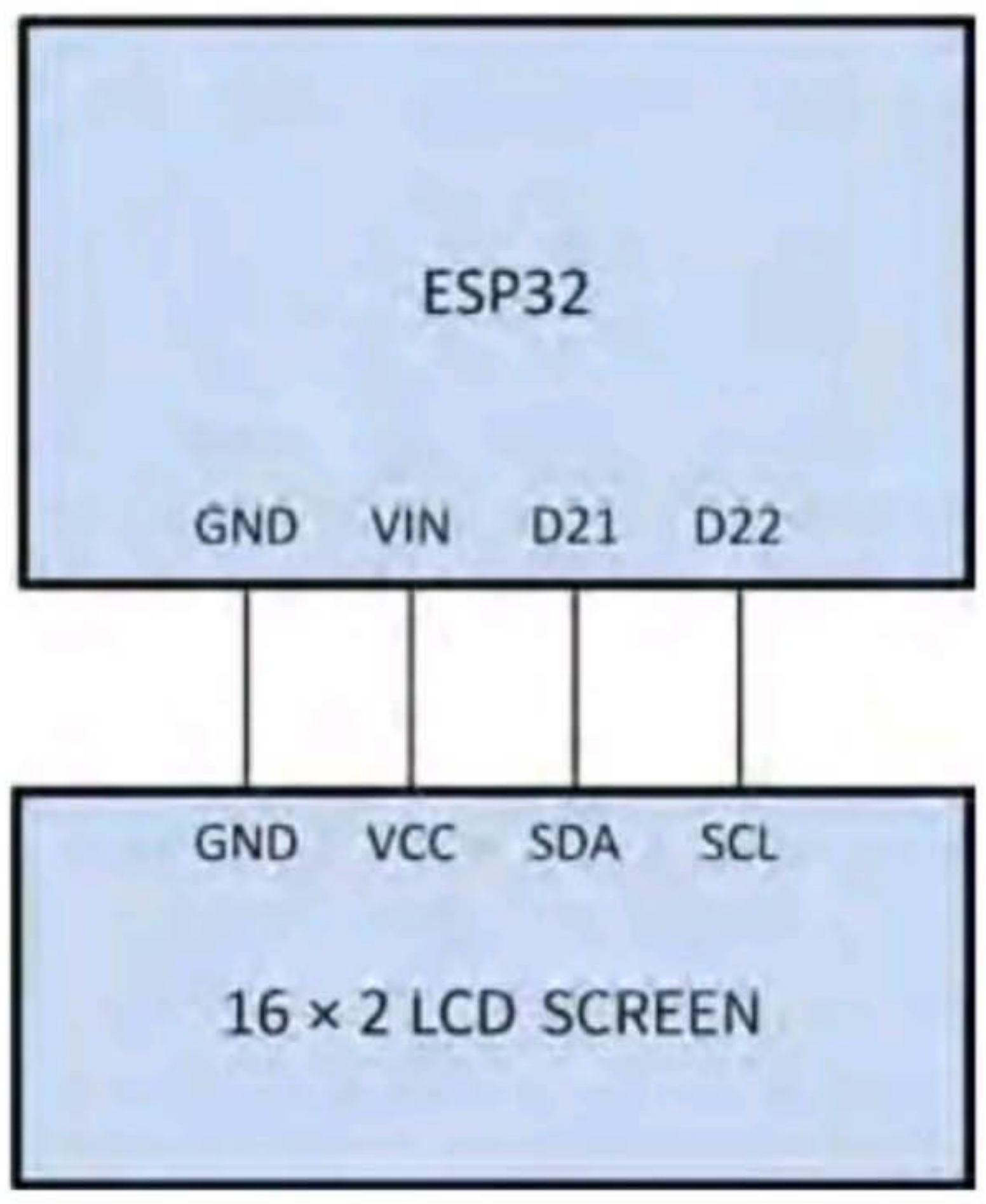


Fig.7.3: Connecting the alphanumeric LCD screen to the ESP32 only requires four wires. Two are for the bidirectional I^2C serial bus (SDA & SCL), while the other two deliver power and provide a common ground for serial communications.

Teach-In Challenge

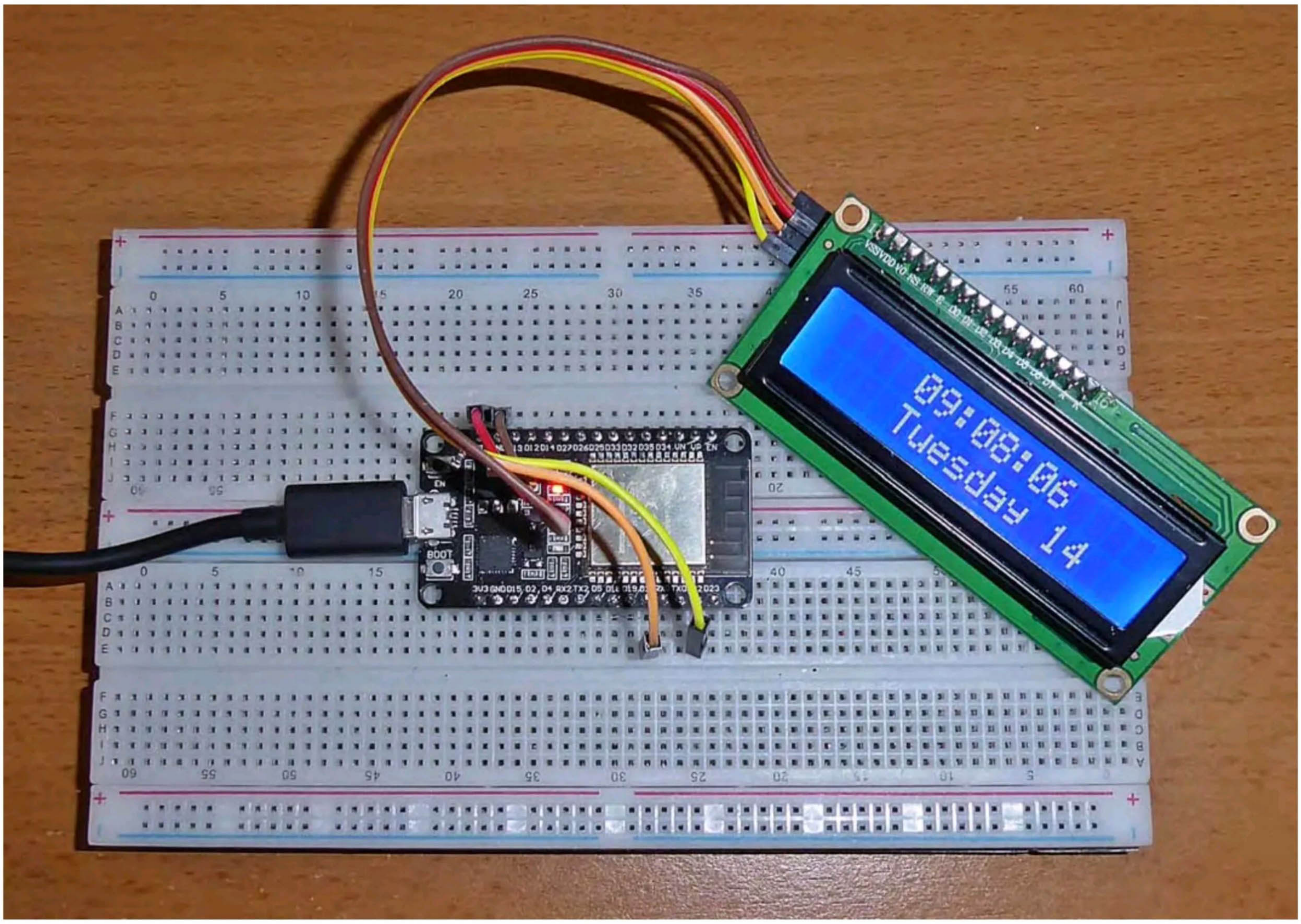
The functionality of this month's Practical Project can easily be extended by adding one or more relays to control external equipment. It can switch this equipment on or off based on the current time and/or date.

Our Teach-In Challenge involves adding a single relay that can be used to control some external night security lighting that's to operate during the period 20:00 to 07:00. The relay (RL1) is similar to those that we met earlier in Part 5 of Teach-In and only requires simple interface circuitry along the lines of that shown in Figs.7.6 and Fig.7.7.

You will need to define the I/O pin for RL1 using a line of the form:

```
// Define the I/O pin
const int LightingRelay = 23;
```

Thereafter, we will be able to control the lighting within a conditional statement using the function call:



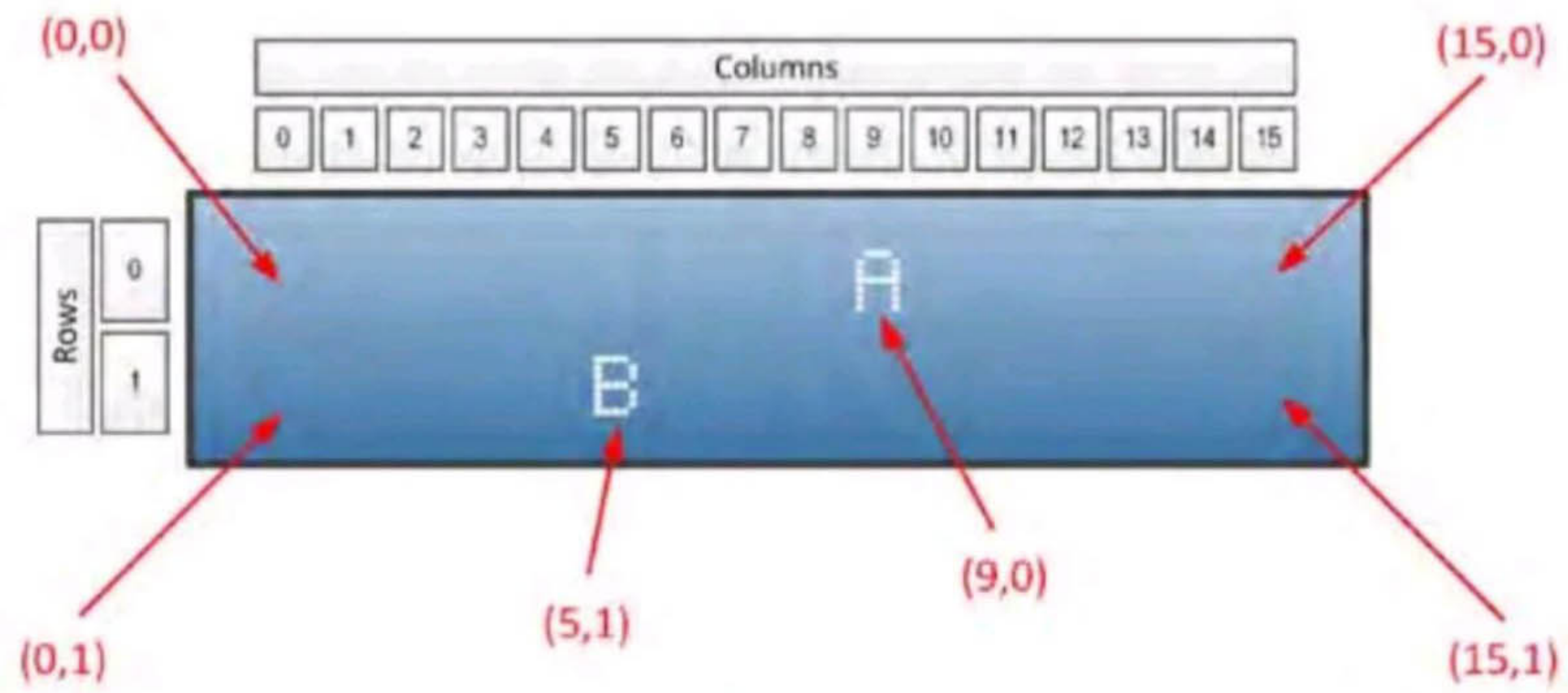

(0,0)
Columns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
(15,0)
Rows
0
1
A
B
(0,1)
(5,1)
(9,0)
(15,1)

Fig.7.4: Characters on the 16×2 LCD are identified by row and column numbers.

```
digitalWrite(LightingRelay, HIGH)
```

... to turn the lighting 'on', and ...

```
digitalWrite(LightingRelay, LOW)
```

... to turn the lighting 'off'. We will leave the conditional statements to you.

Next month

Next month, we will be showing you how to add a low-cost GPS module to your ESP32. This will allow you to use your ESP32 with an inexpensive LCD panel to obtain and display accurate time, location, altitude and speed data.

One important advantage of GPS time over NTP is that it wil work just about anywhere and does not need Internet access.

Coding Workshop will provide you with some pointers to help you develop code to be used with GPS/GNSS (Global Navigation Satellite System) modules and our *Practical Project* will feature a simple GPS/GNSS location fixer. **PE**

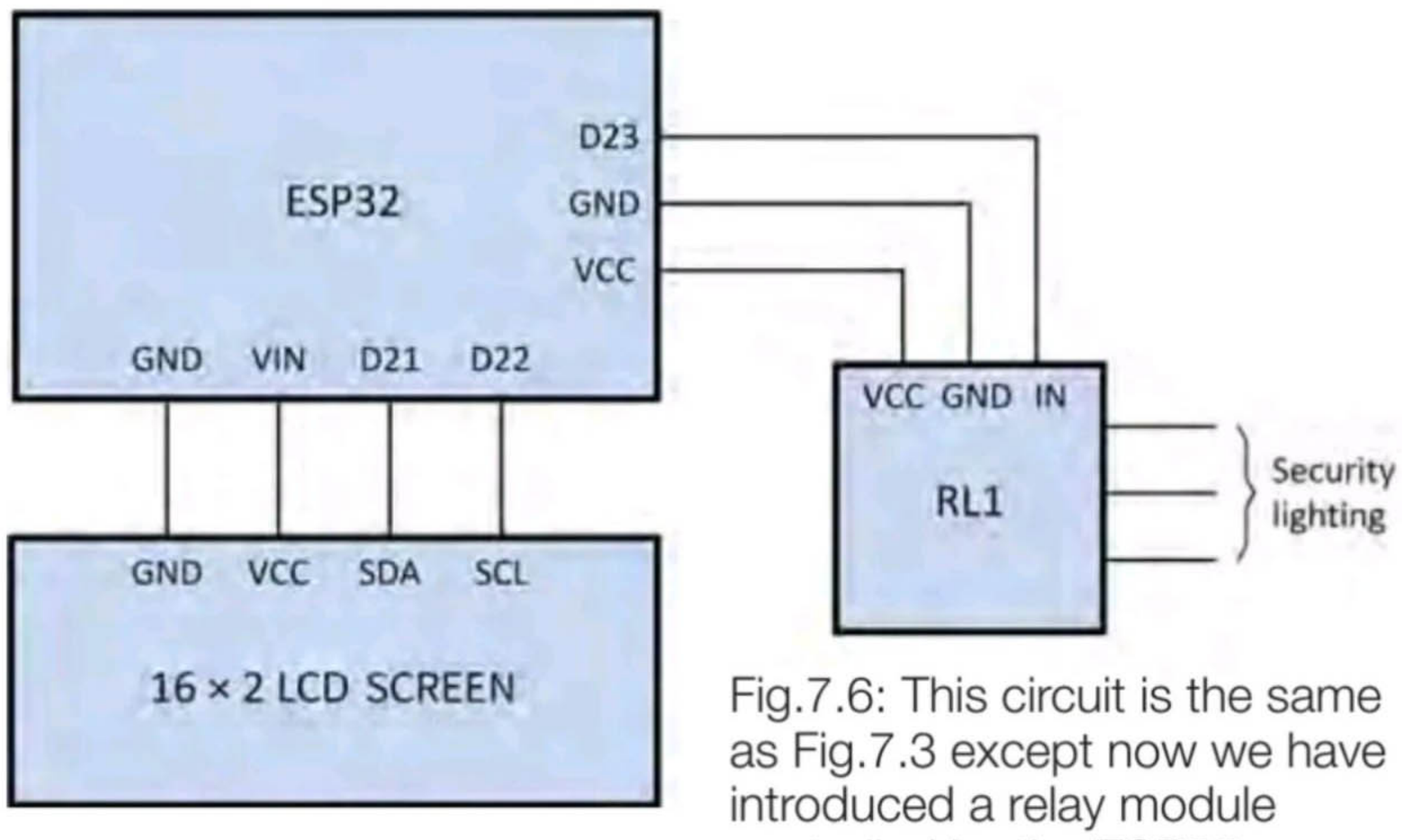

ESP32
D23
GND
VCC
GND
VIN
D21
D22
GND
VCC
SDA
SCL
16 × 2 LCD SCREEN
VCC GND IN
RL1
Security lighting

Fig.7.6: This circuit is the same as Fig.7.3 except now we have introduced a relay module controlled by the ESP32.

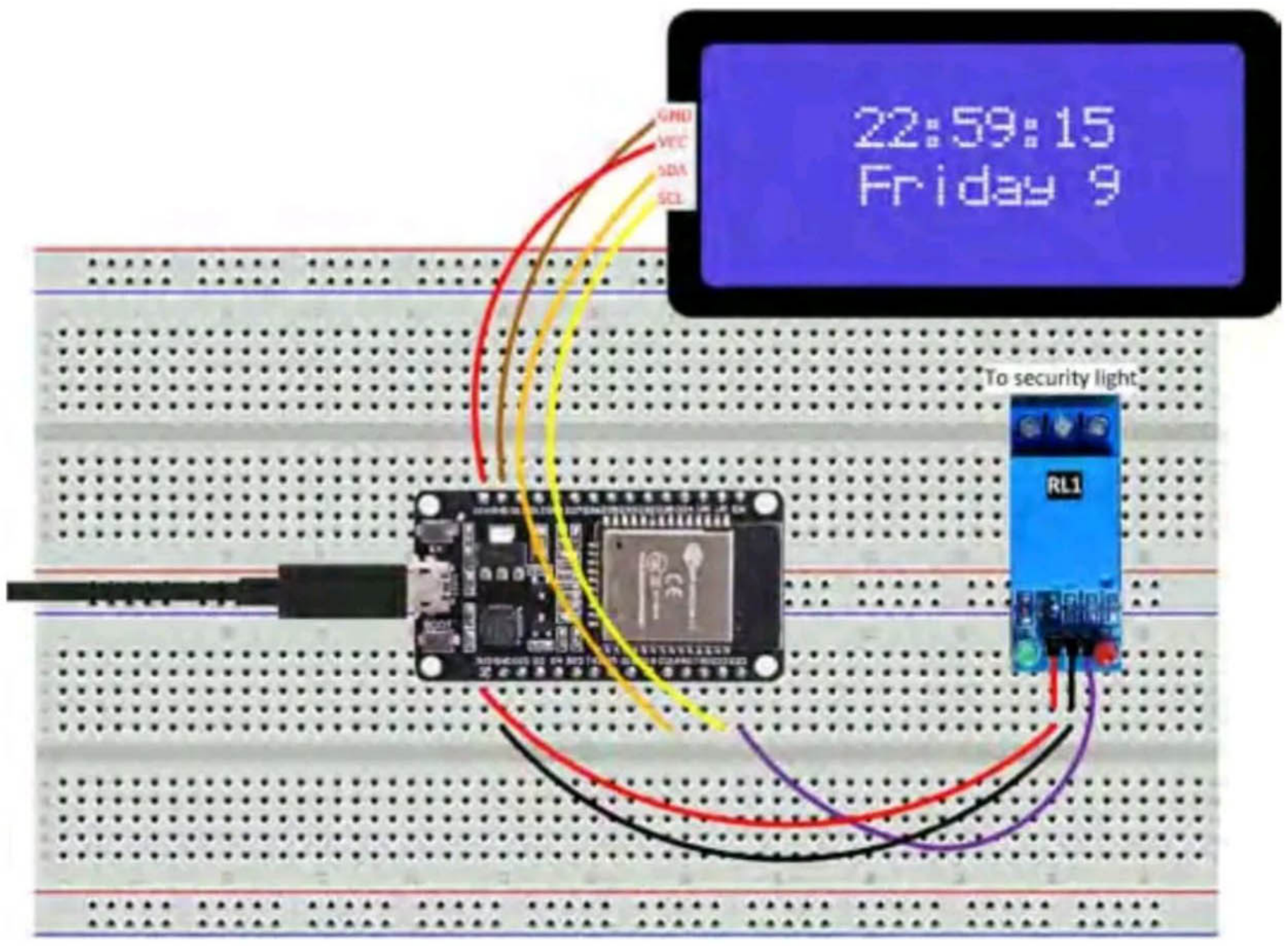

22:59:15
Friday 9
GND
VCC
SDA
SCL
To security light
RL1

Fig.7.7: the relay module requires just three extra wires.

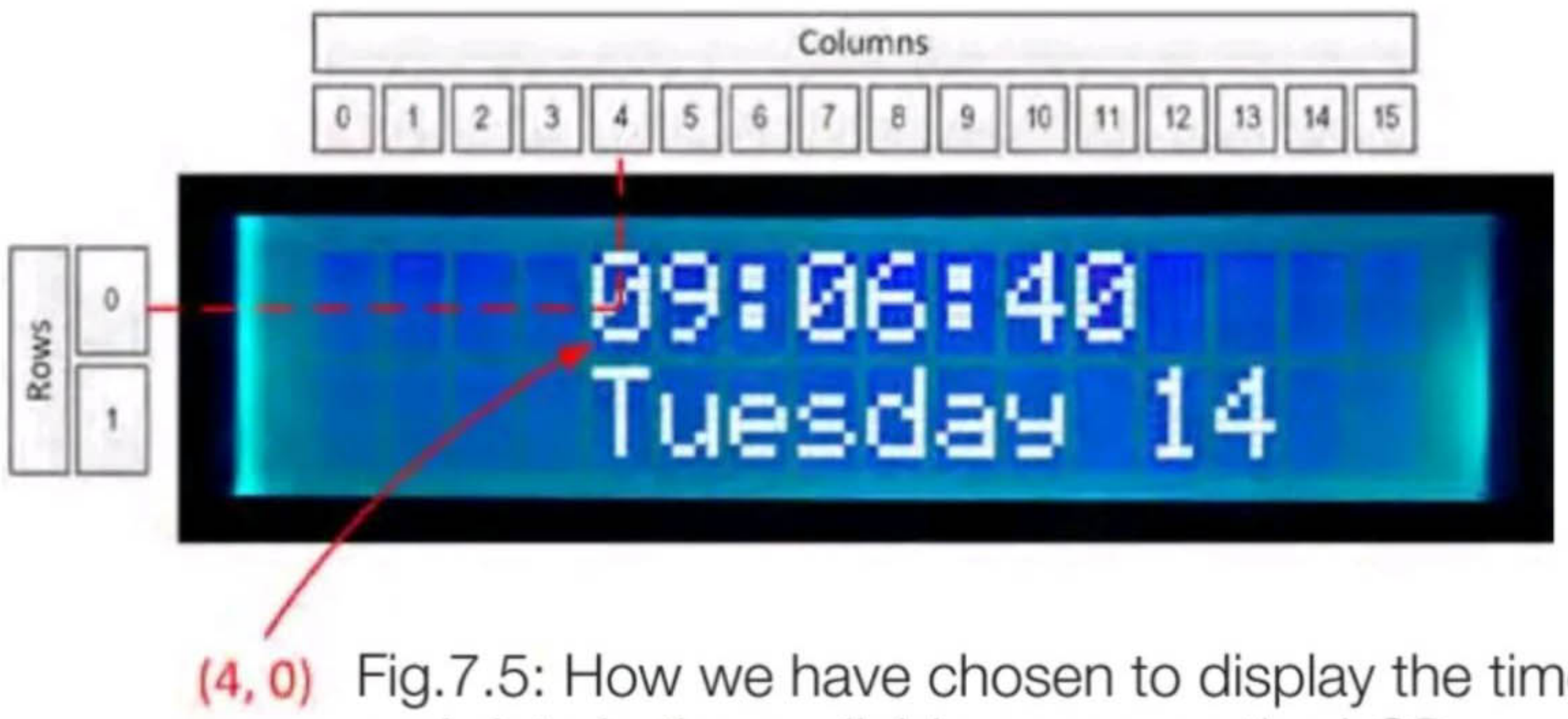

Columns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Rows
0
1
09:06:40
Tuesday 14
(4, 0)

Fig.7.5: How we have chosen to display the time and date in the available space on the LCD.

Listing 7.4 – Code for the ESP32 NTP clock

```
/* Simple ESP32 clock using a 16 x 2 LCD display
and time data obtained from an NTP server. */

// Include the required library files
#include <WiFi.h>
#include "time.h"
#include <LiquidCrystal_I2C.h>

// Define the LCD parameters
int lcdColumns = 16;
int lcdRows = 2;

// Setup the LCD
LiquidCrystal_I2C lcd(0x27, lcdColumns, lcdRows);

// Network parameters
const char* ssid = "YOUR_SSID";
const char* password = "YOUR_PASSWORD";
const char* ntpServer = "pool.ntp.org";
const long gmtOffset_sec = 0;
const int daylightOffset_sec = 3600;

void setup() {
  // Initialise the LCD
  lcd.init();
  // Turn the backlight on
  lcd.backlight();
  // Connect to Wi-Fi
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
   }

  // Initialise and get the time
 configTime(gmtOffset_sec, daylightOffset_sec, ntpServer);
  printLocalTime();

  // Disconnect WiFi
  WiFi.disconnect(true);
  WiFi.mode(WIFI_OFF);
}

void loop() {
  delay(1000);
  printLocalTime();
}

void printLocalTime() {
  struct tm timeinfo;
  // Warn if time is not found
  if (!getLocalTime(&timeinfo)) {
    lcd.setCursor(0, 0);  // First row
    lcd.print("Time not found!");
    lcd.setCursor(0, 1);  // Second row
    lcd.print("Check router?");
    return;
  }
  // Send the time info to the LCD
  lcd.setCursor(4, 0);  // First row
  lcd.print(&timeinfo, "%H:%M:%S");
  lcd.setCursor(4, 1);  // Second row
  lcd.print(&timeinfo, "%A %d");
}
```

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

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PROJECT	CODE	PRICE
JUNE 2021		
Roadies' Test Signal Generator (surface-mount version)	01005201	£8.95
Roadies' Test Signal Generator (through-hole version)	01005202	£9.95
Touchscreen Wide-range RCL Box (Resistor module)	04104201	£18.95
Touchscreen Wide-range RCL Box (Ind/Cap module)	04104202	
KickStart Part 3 – Gyrator-based Audio Filter	KS3-2021	£7.95
MAY 2021		
7-Band Equaliser (Mono)	01104201	£8.95
7-Band Equaliser (Stereo)	01104202	£10.95
Car Altimeter	05105201	£7.95
APRIL 2021		
Reflow Oven – DSP Active Crossover (CPU)	01106193	£19.95
Reflow Oven – DSP Active Crossover (Front panel)	01106195	
Reflow Oven – DSP Active Crossover (LCD)	01106196	
Frequency Reference Signal Distributor	CSE200103	£8.95
MARCH 2021		
Nutube Guitar Effects Pedal	01102201	£12.95
Programmable Thermal Regulator (Peltier Interface)	21109181	£18.95
Programmable Thermal Regulator (Peltier Driver)	21109182	
Tunable HF Preamp	CSE190502	£8.95
FEBRUARY 2021		
4G Remote Monitoring	27111191	£9.95
JANUARY 2021		
Nutube Valve Preamplifier	01112191	£12.95
Arduino DCC Controller	09207181	£10.95
DECEMBER 2020		
Pseudo-Random Sequence Generator	16106191	£7.95
Clever Charger	14107191	£11.95
PE Theremin Amplifier	AO-1220-01	£8.95
NOVEMBER 2020		
LED Christmas Tree (1 off)	16107181-1	£6.95
LED Christmas Tree (4 off)	16107181-2	£14.95
LED Christmas Tree (12 off)	16107181-3	£24.95
LED Christmas Tree (20 off)	16107181-4	£34.95
USB/SPI Interface Board	16107182	£5.95
45V/8A Power Supply PCB *plus* acrylic spacer	18111181	£14.95
45V/8A Power Supply front panel five-way display bezel	18111181-BZ	£3.95
Five-way LCD Panel Meter/Display	18111182	£7.95
OCTOBER 2020		
Digital Audio Millivoltmeter	04108191	£9.95
Precision Signal Amplifier	04107191	£7.95
SEPTEMBER 2020		
PE Theremin PSU	AO-0920-01	£5.95
PE Theremin PSU transformer	AO-0920-02	£7.95
Micromite Explore-28	07108191	£6.95
Ultrabrite LED Driver	16109191	£6.95
AUGUST 2020		
Micromite LCD BackPack V3	07106191	£9.95
Steering Wheel Audio Button to Infrared Adaptor	05105191	£7.95
JULY 2020		
AM/FM/CW Scanning HF/VHF RF Signal Generator	04106191	£13.95
Speech Synthesiser with the Raspberry Pi Zero	01106191	£5.95
PE Mini-organ PCB	AO-0720-01	£14.95
PE Mini-organ selected parts	AO-0720-02	£8.95
High-current Solid-state 12V Battery Isolator – control	05106191	£6.95
High-current Solid-state 12V Battery Isolator FET (2oz)	05106192	£9.95

PROJECT	CODE	PRICE
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Arduino breakout board – 3.5-inch LCD Display	24111181	£6.95
Six-input Audio Selector main board	01110191	£10.95
Six-input Audio Selector switch panel board	01110192	
MAY 2020		
Ultra-low-distortion Preamplifier Input Selector	01111112	£11.25
Ultra-low-distortion Preamplifier pushbutton Input Selector	01111113	
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433MHz Wireless Data Repeater	15004191	£8.50
Bridge-mode Adaptor for Amplifier	01105191	£7.95
iCEstick VGA Terminal	02103191	£5.95
Analogue noise with tilt control	AO-0520-01	£7.95
Audio Spectrum Analyser	PM-0520-01	£8.95
APRIL 2020		
Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
Diode Curve Plotter	04112181	£10.95
Steam Train Whistle / Diesel Horn Sound Generator	09106181	£8.50
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FEBRUARY 2020		
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DSP Active Crossover (DAC) ×2	01106192	
DSP Active Crossover (CPU)	01106193	
DSP Active Crossover (Power/routing)	01106194	
DSP Active Crossover (Front panel)	01106195	
DSP Active Crossover (LCD)	01106196	
JANUARY 2020		
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DECEMBER 2019		
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NOVEMBER 2019		
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Tinnitus & Insomnia Killer (Altronics case – see text)	01110182	£9.95
OCTOBER 2019		
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Opto-isolated Mains Relay (main board)	10107181	£11.50
Opto-isolated Mains Relay (2 × terminal extension board)	10107182	
AUGUST 2019		
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Super Digital Sound Effects Module	01107181	£6.95
Watchdog Alarm	03107181	£8.00
PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
PE Theremin component pack (see p.56, August 2019)	PETY0819	£15.00
JULY 2019		
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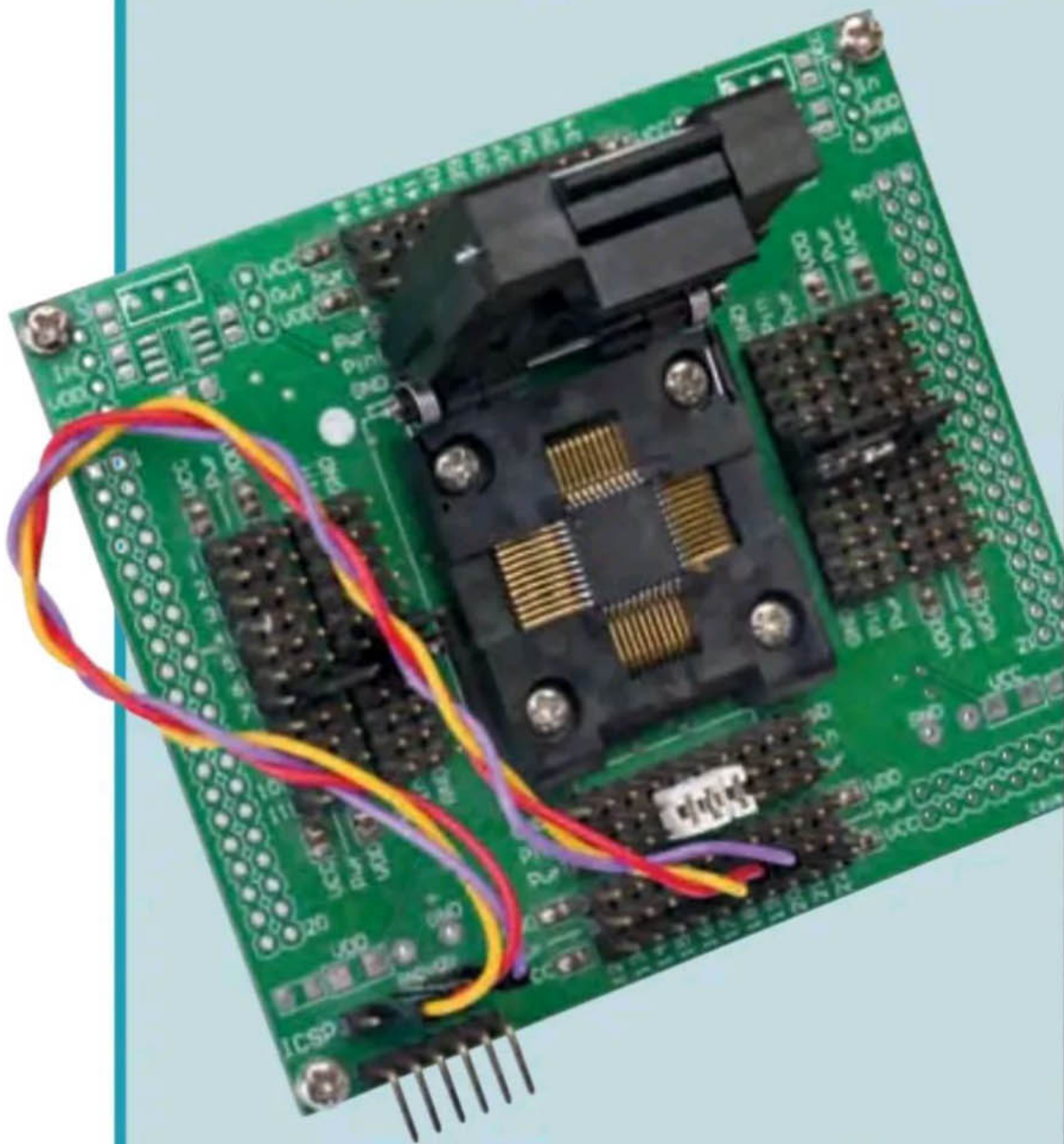

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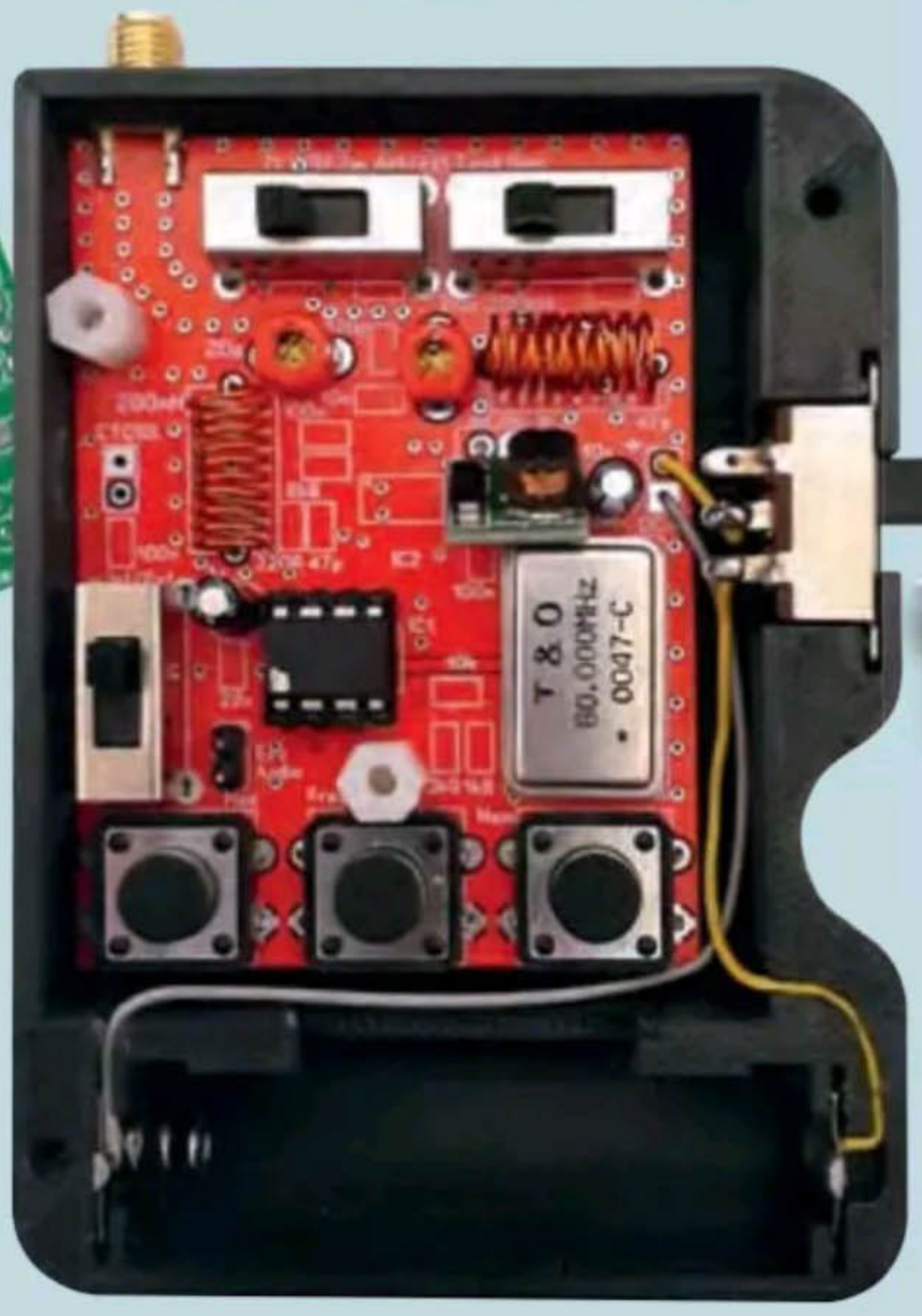

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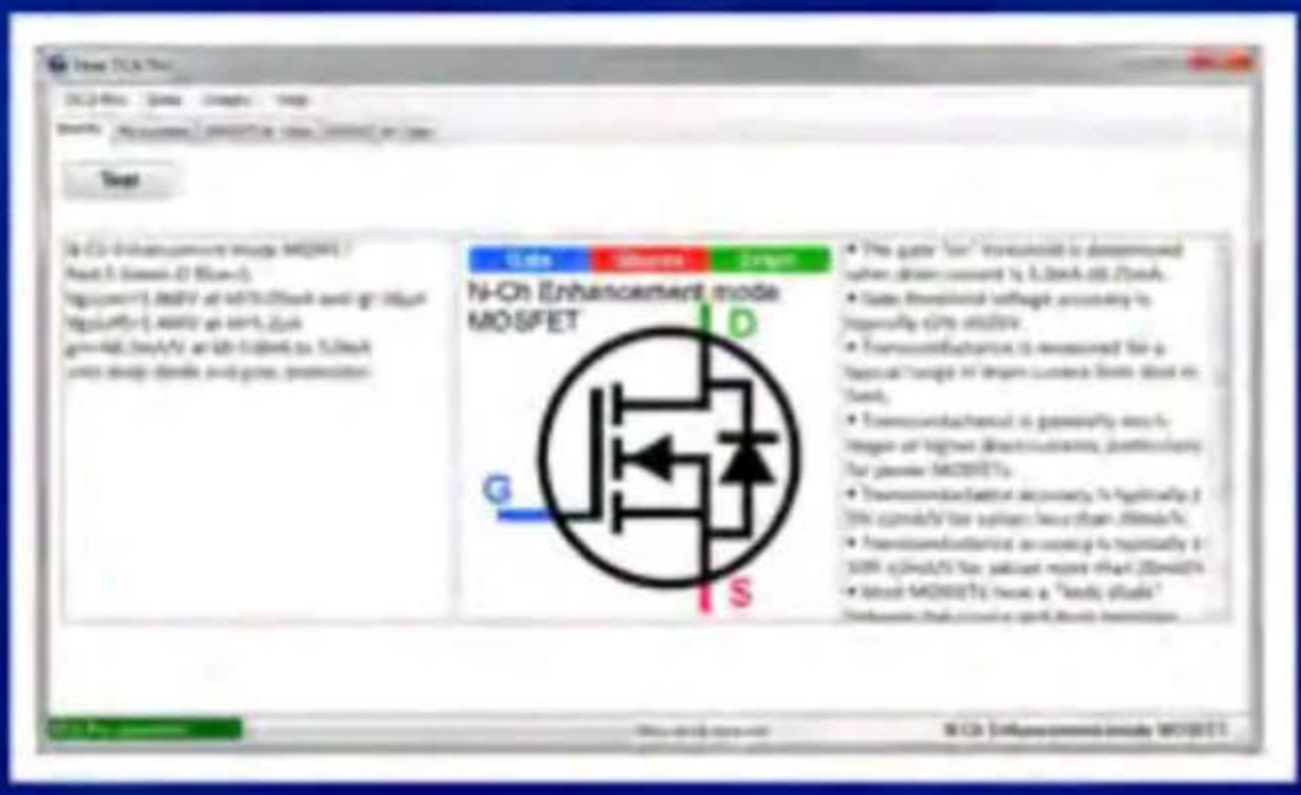
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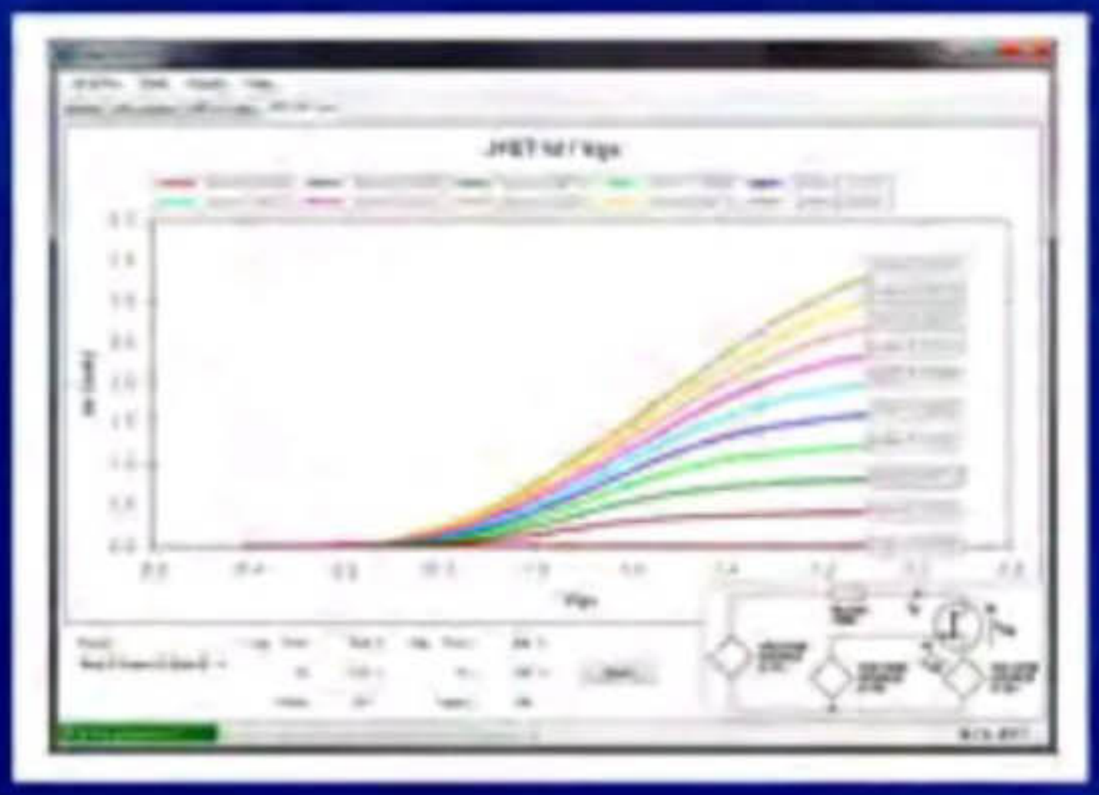

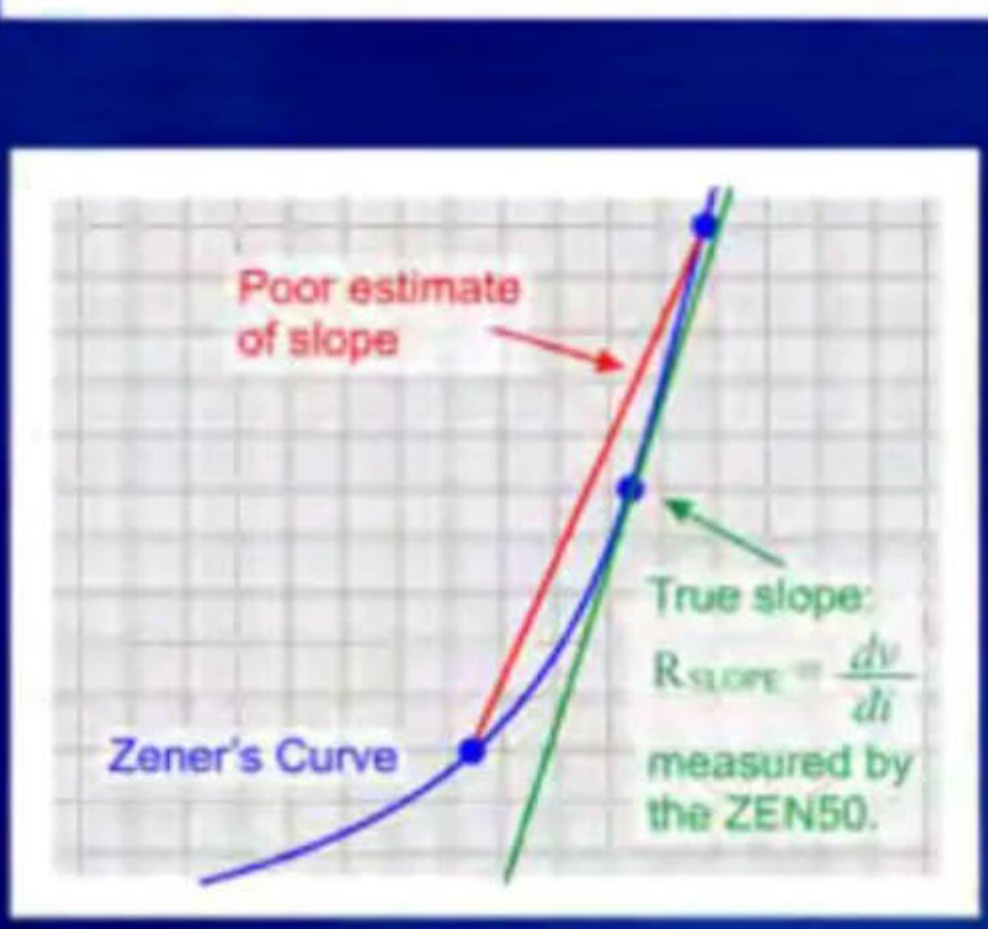

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